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Individual-, System-, and Application-Related Factors Influencing the Perception of Virtual Humans in Virtual Environments

Dissertation

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To my beloved parents, who had to leave too soon,
and to Hanskarl, who had to leave so suddenly.

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Abstract

Mixed, augmented, and virtual reality, collectively known as extended reality (XR), allows users to immerse themselves in virtual environments and engage in experiences surpassing reality's boundaries. Virtual humans are ubiquitous in such virtual environments and can be utilized for myriad purposes, offering the potential to greatly impact daily life. Through the embodiment of virtual humans, XR offers the opportunity to influence how we see ourselves and others. In this function, virtual humans serve as a predefined stimulus whose perception is elementary for researchers, application designers, and developers to understand. This dissertation aims to investigate the influence of individual-, system-, and application-related factors on the perception of virtual humans in virtual environments, focusing on their potential use as stimuli in the domain of body perception. Individual-related factors encompass influences based on the user's characteristics, such as appearance, attitudes, and concerns. System-related factors relate to the technical properties of the system that implements the virtual environment, such as the level of immersion. Application-related factors refer to design choices and specific implementations of virtual humans within virtual environments, such as their rendering or animation style.

This dissertation provides a contextual framework and reviews the relevant literature on factors influencing the perception of virtual humans. To address identified research gaps, it reports on five empirical studies analyzing quantitative and qualitative data from a total of 165 participants. The studies utilized a custom-developed XR system, enabling users to embody rapidly generated, photorealistically personalized virtual humans that can be realistically altered in body weight and observed using different immersive XR displays. The dissertation's findings showed, for example, that embodiment and personalization of virtual humans serve as self-related cues and moderate the perception of their body weight based on the user's body weight. They also revealed a display bias that significantly influences the perception of virtual humans, with disparities in body weight perception of up to nine percent between different immersive XR displays. Based on all findings, implications for application design were derived, including recommendations regarding reconstruction, animation, body weight modification, and body weight estimation methods for virtual humans, but also for the general user experience. By revealing influences on the perception of virtual humans, this dissertation contributes to understanding the intricate relationship between users and virtual humans. The findings and implications presented have the potential to enhance the design and development of virtual humans, leading to improved user experiences and broader applications beyond the domain of body perception.

Contents

Synopsis

> *Every reality, every fulfilled presence, consists of two halves, subject and object. If the objective half is completely the same, but the subjective half is different, the present reality is completely different.*
>
> *(Arthur Schopenhauer, 1788 – 1860)*

In the 19th century, philosopher Arthur Schopenhauer already reflected on the concept of perception and its role in shaping our understanding of reality. He noted that subjective interpretation shapes the perception of supposedly objective reality and that this can lead to entirely different experiences for individuals (Schopenhauer, 1904). What originally related to the perception of reality can also be applied to the perception of extended reality (XR) in the present day. Even when the objective half (the virtual environment) is completely the same, the subjective half (the user's experience) can differ considerably depending on the user's individual perspective, emotions, habits, and prior experiences that lead to a completely different understanding of the virtual environment (Latoschik & Wienrich, 2022).

However, there is an essential difference between reality and XR. In XR, the perception is not only shaped by subjective interpretation but also by the fact that artificially generated content is inevitably conveyed through a particular medium. Therefore, the system characteristics of the medium used and the design of the application can play a significant role in shaping the user's experience (Skarbez et al., 2021b). Those factors also apply to an omnipresent part of our perception, the human being. Whether in reality or XR, we are always surrounded by human beings, or rather, human bodies. There are situations where we meet other human beings, but even when we are not in any social interaction, we constantly face our own physical representation, our body. Accordingly, virtual humans can also be an elementary component of virtual environments, regardless of whether they are supposed to represent others or ourselves. To facilitate their use in XR, the here presented dissertation explores how various individual-, system-, and application-related factors influence the visual perception of virtual humans in virtual environments and how this can shape the overall user experience. The subsequent sections first introduce fundamental concepts and theories, provide insight into relevant application scenarios of virtual humans, and formulate the concrete research question of this dissertation. They further present a review of pertinent related work, summarize the dissertation's respective chapters, and discuss their joint contributions.

Experiencing Virtual Environments in XR

Virtual Environments (VEs) are artificial, computer-generated worlds that allow users to encounter and interact with digital content in ways that simulate or mimic reality-like experiences from a first-person perspective in real-time (Burdea & Coiffet, 2003; LaViola et al., 2017). These environments are nowadays mainly generated using modern real-time interactive system development platforms (also known as game engines) like Unity (Unity Technologies, 2020) or Unreal (Epic Games, 2021b). VEs are primarily conveyed using different display systems, ranging from lower immersive smartphone or desktop systems to complex higher immersive XR systems. This dissertation focuses on the use of immersive XR systems for experiencing VEs, where XR serves as an overarching term, including mixed reality (MR), augmented reality (AR), and virtual reality (VR) systems (Doerner et al., 2022). The user experience (UX) of such XR systems results from the sum of all perceptions and reactions a user has during and after interaction with the system and composes of hedonic qualities, such as the user's joy during an experience, and pragmatic qualities, such as the user's interaction efficiency (International Organization for Standardization, 2019). It is further recommended to include XR domain-specific qualia, such as immersion and presence (Tcha-Tokey et al., 2016; Wienrich & Gramlich, 2020), which will be presented in the remainder of this dissertation.

Immersion and Presence

According to the widely accepted definition of Slater and Wilbur (1997), an XR system's degree of immersion is shaped by the system's objective physical characteristics and its ability to deliver a surrounding, vivid, extensive, and inclusive experience of a VE to its user. A surrounding XR experience can be achieved, for instance, by providing a large visual field of view (Hendrix & Barfield, 1996a; J.-W. Lin et al., 2002), while its vividness can be influenced by the fidelity and resolution of the rendered content (Bracken, 2005; Welch et al., 1996). The extensiveness refers mainly to the multisensory integration (Ernst, 2008) of visual perception and proprioception (Hendrix & Barfield, 1996a; T. L. Wu et al., 2019), later described as sensorimotor contingencies (Slater, 2009), that establish a range of supported user actions influencing the perception of a VE and its content (e.g., when the rendered perspective changes according to the head movements). However, multisensory contingencies can also occur between other sensory perceptions like audio (Hendrix & Barfield, 1996b), haptic (Kreimeier et al., 2019), temperature (Ranasinghe et al., 2017), or taste and smell (Weidner et al., 2023b). Finally, the inclusiveness of a system defines the extent to which a system can exclude physical reality, which can also be related to the taxonomy of visual MR displays introduced by Milgram and Kishino (1994). The taxonomy describes the progression between perceiving purely physical reality and ultimate VR along a reality-virtuality continuum with increasing immersiveness of the used display. The area in which real and virtual content blend over each other is defined as MR and divided into AR and augmented virtuality. MR experiences can be realized using various displays systems, including CAVE-like AR projectors (Cruz-Neira et al., 1992), screen-based fish tank AR (Ware et al., 1993), or AR head-mounted displays (HMDs) using either optical see-through (OST) or video see-through (VST) technology (Caudell & Mizell, 1992; Edwards et al., 1993; Sutherland, 1968). Pure VR experiences, on the other hand, are implemented using closed VR HMDs (Angelov et al., 2020) that shut out the visual perception of physical reality. Slater and Wilbur (1997) further named the user's sense of presence (SoP), originally defined as the sense of really "being there" in a VE (Heeter, 1992, p. 4), as the major quale for quantifying the subjective reaction to encountering an XR experience and expected it to be affected by an XR system's degree of immersion. Over the years, various empirical works have confirmed this assumption (Chicchi Giglioli et al., 2019; Cummings & Bailenson, 2016; Waltemate et al., 2018). In the practical application of XR, a high level of SoP is considered crucial for eliciting decisive behavioral, cognitive, and emotional responses to the presented content of a VE (Diemer et al., 2015; Krijn et al., 2004; Rothbaum, 2006; Wienrich et al., 2021a).

An Update on Presence and Related Concepts

To date, the concepts of immersion and SoP are still the widely used status quo for categorizing and describing XR experiences. However, the technological capabilities for implementing XR systems and the research on the nature of UX in VEs have steadily advanced over the past decades and made an update of related concepts timely. Skarbez et al. (2021b) revisited Milgram's reality-virtuality continuum reflecting the latest research and developments on the classification of XR experiences (Skarbez et al., 2017; Slater, 2009; Speicher et al., 2019) and proposed a revised version of a taxonomy for describing XR experiences consisting of three dimensions: immersion, coherence, and extent of world knowledge (see Figure S1). The revised taxonomy goes beyond merely considering visual perceptions by incorporating all external senses into the classification and enclosing the subjective feelings that users are expected to experience. The dimension of immersion follows the above-introduced definition widely and ranges from systems that do not provide any virtual content to systems that support all conceivable physical user actions causing the feeling of "being there" named as spatial presence, also known as place illusion. The dimension of coherence refers to the conformity of different sensory information a user perceives during an XR experience, ranging from totally inconsistent virtual behavior to entirely plausible experiences, causing the user's subjective feeling of plausibility, also known as plausibility illusion. The dimension extent of world knowledge describes the degree of the physical reality a system incorporates into an XR experience ranging from a completely self-sufficient and abstract world to a completely real-world replica that supports the user's awareness of the real world. Over the decades, numerous other concepts and terms emerged around the idea of presence. However, as these have not been considered in the latter of this dissertation, the reader is referred to the comprehensive summary of existing concepts and their synonyms by Skarbez et al. (2017) for further information.

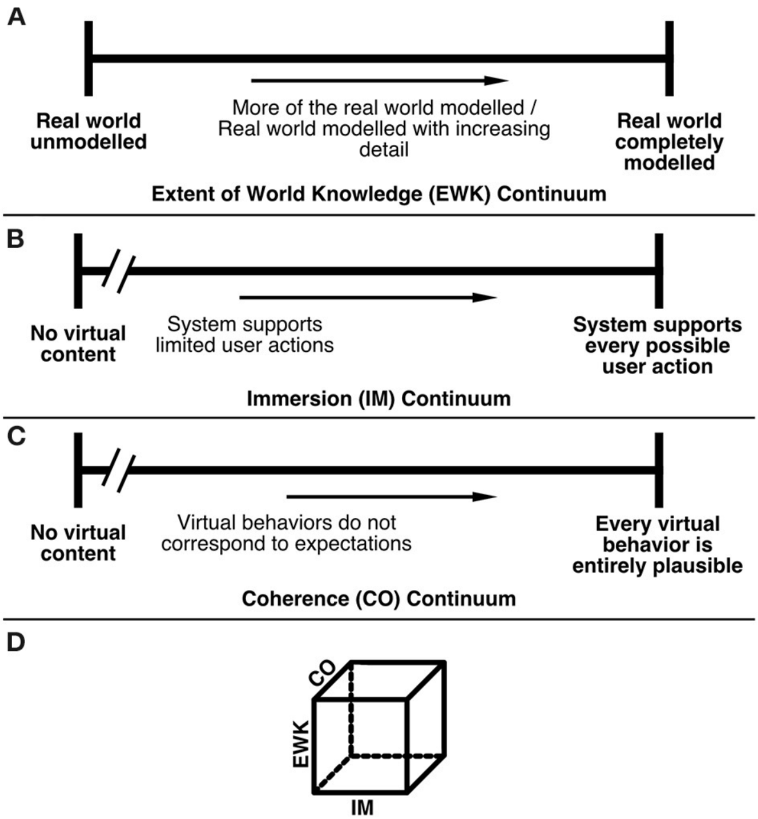

Figure S1: Illustration of Skarbez et al.'s revised taxonomy showing the dimensions extent of world knowledge (A), immersion (B), and coherence (C), as well as the interrelation between the three (D). The figure has been taken from Skarbez et al. (2021b).

Beyond Presence: Congruence and Plausibility

An alternative approach for describing XR experiences is the congruence and plausibility (CaP) model recently published by Latoschik and Wienrich (2022). It focuses explicitly on congruences between the user's sensory input and expected information, leading to a subjective interpretation of the plausibility of an XR experience that finally reflects in XR-related qualia like SoP (see Figure S2). The model consists of a three-layered manipulation space distinguishing between the potentially bottom-up processed sensory and perceptual layers, and the top-down processed cognitive layer, each defining a different route for processing sensory input received during an XR experience. The sensory layer sets the individual boundary conditions for information processing by unconsciously converting physical and physiological signals into neural signals that receive and derive their congruences from life-long habituated biological and physiological knowledge. Therefore, certain interindividual differences

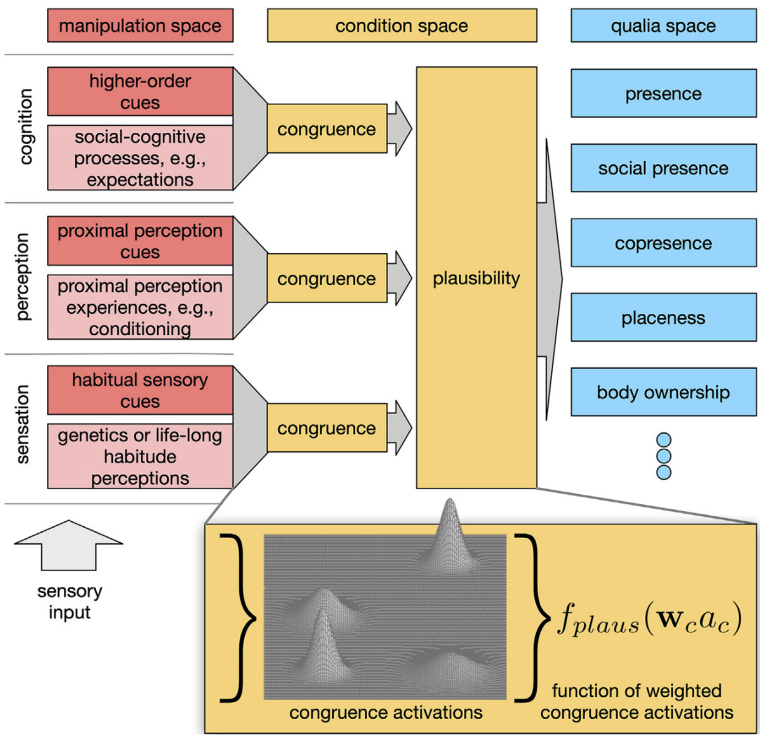

Figure S2: Illustration of Latoschik and Wienrich's congruence and plausibility model depicting the progression from the users' sensory input to their subjective response. The figure has been taken from Latoschik and Wienrich (2022).

in perception and cognition of XR experiences can potentially be attributed to this layer but are challenging to manipulate. The perceptual and cognitive layers, however, exhibit greater plasticity as they are influenced by prior knowledge, memories, or mental models that allow the XR experience's adaption in congruence to the user's expectations for achieving plausibility concerning particular XR qualia. For example, spatial presence is expected to result from a spatially plausible XR experience caused by a strong congruence between the provided device-specific spatial cues and the user's expectation of a spatial experience, while a high realism of the XR experience might result from a plausible rendering of virtual objects in congruence to what a user is used to see in reality. Due to its novelty, there has been little empirical work verifying the CaP model so far. However, the first studies confirm the model's assumptions on the multi-layer nature of plausibility in XR experiences (Brübach et al., 2022; Westermeier et al., 2023), also including the role of virtual humans (Mal et al., 2022, 2023) as further outlined in the following sections.

Virtual Humans in Virtual Environments

The literature presents countless diverse definitions of virtual humans, their capabilities, and their nomenclature (Burden & Savin-Baden, 2019; Doerner et al., 2022; Nowak & Fox, 2018). For example, while Burden and Savin-Baden (2019) see virtual humans as digital entities, algorithms, or programs that appear, think, feel, and behave like humans, others define them as a general term for describing human-like objects in VEs (Doerner et al., 2022). In this dissertation, virtual humans (also known as virtual characters or virtual representations) are defined as artificial, computer-generated digital entities or models of human beings that can be displayed and animated within VEs. Depending on their context of use and appearance, their designation may further change. This work follows Bailenson and Blascovich (2004) and distinguishes between virtual humans used as embodied agents and avatars. Embodied agents represent virtual humans controlled by algorithms or prerecorded animations, while avatars are associated with specific users who control them. The term virtual alter ego is further used for virtual humans that are personalized in appearance to particular users but do not necessarily need to be controlled by them. Figure S3 shows the genesis of a virtual human as an alter ego and its use as an avatar and embodied agent. However, it is worth noting that there can be some overlap between the introduced terms, and they may be used interchangeably depending on their specific definition in the context of a work. Therefore, the present work considers the conceptualization and operationalization of virtual humans in others' work, as suggested by Nowak and Fox (2018), and implicitly homogenizes them according to the introduced definitions in order to draw correct conclusions.

Figure S3: The top shows the generation of a virtual human (left) using the approach for rapid reconstruction of photorealistically personalized alter egos by Achenbach et al. (2017) and its results in comparison to the model (right). The bottom highlights the virtual human's use as embodied agent (left), where the controllers represent the user, and as embodied avatar (right), where the avatar represents the user.

The idea of using virtual humans in VEs dates back to the 1960s when the first mathematical models (Hanavan Jr, 1964) and visual representations (Dooley, 1982) of human bodies were developed for simulation and anthropometric modeling in human factors. However, their use in areas such as entertainment (Lugrin et al., 2018; Valve, 2020a), education (Lugrin et al., 2016; Scavarelli et al., 2021), and mental health (Matamala-Gomez et al., 2021; O'Connor, 2019) has quickly become established over the years. The reader is referred to the work of Burden and Savin-Baden (2019) for a comprehensive overview. While creating virtual humans was tedious manual labor in the early days, developments in computer graphics have significantly improved the generation speed and quality of both generic virtual humans (Autodesk, 2014; Gonzalez-Franco et al., 2020a) and personalized virtual alter egos (Crossley et al., 2012; Pujades et al., 2019). By using recently established reconstruction methods, it even has become feasible to generate photorealistic virtual humans (DAZ Productions, 2005; Epic Games, 2021a) or virtual alter egos (Achenbach et al., 2017; Bartl et al., 2021b; Wenninger et al., 2020) in a short period (see Figure S3, top).

Nowadays, virtual humans have become an integral part of XR experiences' visual content. They can exhibit different visual appearances and behaviors depending on their desired function. Generic-looking virtual humans showing generic behavior as embodied agents can create a specific atmosphere within an XR experience, for example, when training in public speaking (Glémarec et al., 2022) or simulating group dynamics (Neyret et al., 2020b). On the other hand, generic virtual humans employed as embodied avatars are often used to induce behavioral adaptations based on the Proteus effect (Yee & Bailenson, 2007; Yee et al., 2009), as later addressed in the section on the embodiment of virtual humans. Personalized virtual alter egos used as embodied avatars (see Figure S3, bottom right) are particularly useful for applications requiring users to maintain their identity within a VE (Mystakidis, 2022; Sampaio et al., 2021). Finally, virtual alter egos used as embodied agents (see Figure S3, bottom left) can highlight the users' appearance or behavior from an allocentric perspective fostering their self-reflection (Fiedler et al., 2023b; Neyret et al., 2020a; Thaler et al., 2019). Overall, the use cases for virtual humans in XR are almost countless and always require their contextual adaption in congruence with the user's expectations, which can have a considerable impact on their perception and the overall plausibility of an XR experience (Latoschik & Wienrich, 2022; Mal et al., 2022, 2024b). This topic will be further addressed in the section on potential factors influencing the perception of virtual humans in VEs.

Virtual Humans to Support Body Perception

Among the countless use cases for virtual humans in XR experiences, this dissertation focuses primarily on their use in the domain of mental health applications. In particular, it concentrates on use cases that can support a positive perception of the own physical body. This application area shows great relevance, as a negative or distorted perception of our body can seriously affect our mental well-being. For example, it can manifest in body shape concerns (Kamaria et al., 2016), diminished self-esteem (O'Dea, 2012), or body dissatisfaction (Spreckelsen et al., 2018), which might translate into body-related disorders like body dysmorphic disorder (Kaplan et al., 2013), obesity (J. K. Thompson & Tantleff-Dunn, 1998), or eating disorders (Cash & Deagle III, 1997). The conventional treatment of these severe consequences often faces high relapse rates (Fildes et al., 2015; Khalsa et al., 2017), which motivates research of novel treatment methods. Such an alternative can be the support by

Figure S4: Exemplary illustration of a body weight modification performed on the virtual human from Figure S3. The modifications are based on an improved version of the approach by Piryankova et al. (2014a). Each step represents a change of two BMI points.

virtual humans in XR, which has shown great potential in recent years (Horne et al., 2020; Matamala-Gomez et al., 2021; Portingale et al., 2024; Turbyne et al., 2021). For example, the ViTraS research project[1], in the context of which this dissertation was conducted, aimed to research and develop approaches to support body perception by stimulating a modulated self-perception (Döllinger et al., 2019). One idea is to expose affected individuals within XR experiences to their own bodies using personalized virtual humans. This approach differs from established real-life mirror exposure (Delinsky & Wilson, 2006; Griffen et al., 2018), as the virtual representations can be modified in outer appearance. For instance, advanced statistical models can simulate realistic changes in body weight (Hudson et al., 2020; Maalin et al., 2020; Piryankova et al., 2014a) to create predefined artificial stimuli (see Figure S4) that can help to expose and illustrate the mental perception of the user's body, showcasing their successful weight loss outcomes, or focusing intensely on their present and desired body weight (Döllinger et al., 2019; Riva et al., 2019). Those stimuli can further support fundamental research on human body perception (Mölbert et al., 2018; Thaler et al., 2018a, 2018b). However, when using virtual humans as predefined stimuli, their visual perception plays an even more significant role, as a misperception could lead to false impressions and uncontrolled experiences, ultimately worsening a present negative or distorted body perception. Therefore, understanding and considering influencing factors appears critical when designing applications intended to effectively support positive body perception, as concealed influences of unexplored factors could compromise desired outcomes.

[1] https://www.hci.uni-wuerzburg.de/projects/vitras/

Embodiment of Virtual Humans to Support Change Efforts

For working on body perception, the embodiment of virtual humans within VEs is a fundamental concept to consider. When referring to virtual human embodiment in this dissertation, we specifically denote the process of embodiment, where a user literally slips into the outer shell of the virtual human within an XR experience (de Vignemont, 2011). It allows users to perceive the virtual human as their own virtual body, observing it like their real body from their first-person perspective or in a virtual mirror from a third-person perspective (Debarba et al., 2015; Inoue & Kitazaki, 2021). Therefore, the definition of virtual human embodiment needs to be distinguished from the mere control of virtual humans, such as known from lower-immersive computer games (Klevjer, 2012), and from the user's subjective reaction that may arise as a consequence of embodying a virtual human, the sense of embodiment (SoE). According to the widely accepted definition of Kilteni et al. (2012), SoE describes the feeling of owning, controlling, and being inside a virtual body or body parts and is divided into the dimensions of virtual body ownership (VBO), agency, and self-location, respectively. The concept originated from the fundamental findings of the rubber hand illusion, referring to the assimilation of foreign objects into a person's body schema through visuotactile coherence. Thereby, SoE occurs when a person receives synchronous tactile stimulation on both a real and an artificial body part while only being able to observe the artificial body part (Botvinick & Cohen, 1998; Tsakiris & Haggard, 2005). Subsequent studies have replicated these findings using pure virtual body parts (IJsselsteijn et al., 2006; Kocur et al., 2022) and extended it to encompass entire virtual bodies in VR (Slater et al., 2010b). Slater et al. (2009) further demonstrated that visuomotor coherences may also lead to the SoE. To achieve this, the body parts of the virtual human move in the users' field of view in synchrony with their real movements, usually captured in real time using a motion-tracking solution (Spanlang et al., 2014). Inducing the effect is often supported by virtual mirrors, which can provide an additional holistic view of the virtual body (Inoue & Kitazaki, 2021; Kilteni et al., 2012). Figure S5 shows an example of virtual human embodiment in VR on the left.

In fully immersive VR, where users typically have no visual reference to their physical bodies, providing a virtual body can enormously impact the user's experience in different ways. For example, prior work has shown that virtual human embodiment can lead to increased SoP (Waltemate et al., 2018), higher accuracy and performance (S. Jung & Hughes, 2016; Pastel et al., 2020), improved spatial perception (Leyrer et al., 2011; Mohler et al., 2010; Ries et al., 2008), or reduced cognitive load when executing experimental tasks (Steed et al., 2016). Additionally, it is considered to intensify the emotional response to the con-

Figure S5: Comparison between virtual human embodiment in VR (left) and AR (right). The pictures have been taken from the material of Wolf et al. (2020).

tent provided by a VR application (Gall et al., 2021), which can be particularly useful when confronted with the own body in body perception scenarios. For further information, the reader is referred to the systematic literature review and meta-analysis on the effectiveness of virtual human embodiment in VR by Mottelson et al. (2023). In light of the CaP model (Latoschik & Wienrich, 2022), the advantages of virtual human embodiment come as no surprise since the visual presentation of a virtual body with similar proportions moving in synchrony to our real body matches our real-world expectations. These congruences lead to a plausible experience that allows us to apply priorly acquired world knowledge within the VE and ultimately impact the user's subjective response in the qualia space (i.e., the mentioned improved spatial perception or the reduced cognitive load). Increasing plausibility by virtual human embodiment can also lead to more realistic and meaningful experiences, which might help achieve desired behavioral or attitudinal adaptation effects when targeting body perception (Wienrich et al., 2021a).

One mechanism that significantly benefits from the embodiment of virtual humans to induce such adaptions is the Proteus effect. The effect has first been observed by Yee, Bailenson, and colleagues (Yee & Bailenson, 2007; Yee et al., 2009) and describes the phenomenon that users' behavior or attitude can be influenced by the stereotypes associated with the appearance and behavior of the avatar they embody. To illustrate the effect, the authors drew the analogy to soldiers, who behave differently, once they wear a uniform. In the following years, various studies have shown the potential of the effect, for example, for reducing implicit racial bias (Banakou et al., 2016; Peck et al., 2013), increasing cognitive (Banakou et al., 2018) and physical performance (Kocur et al., 2020; Mal et al., 2023), or manipulating responses to pain (Matamala-Gomez et al., 2019). Concerning the behavioral manipulation through the embodiment of avatars with altered body weight, Dupraz et al. (2023) showed, for example, that participants embodied in an avatar with overweight needed more time to perform a locomotor imagery task than when embodied in a normal-weight avatar. Further research has discovered that the individually elicited SoE can be a strong moderator for inducing the Proteus effect (Kilteni et al., 2013; Mal et al., 2023). For a comprehensive overview of the outcomes of the Proteus effect, the reader is referred to the works of Ratan et al. (2020) and Praetorius and Görlich (2020).

There are also examples where perceptional adaptions have been observed due to the embodiment of differently shaped avatars, which are particularly interesting for working on body perception. For example, Banakou et al. (2013) found that being embodied in the virtual body of a child can lead to an overestimation of virtual objects presented in a VE. Normand et al. (2011) showed that embodying a generic avatar with an enlarged belly can lead to changes in assessing the user's actual belly size. Piryankova et al. (2014b) expanded on these findings by demonstrating changes in body size perception when embodying an avatar with a different body size from an egocentric perspective using affordance and body size estimation tasks. However, since the original definition of the Proteus effect relates more to behavioral and attitudinal adaptions, this observed effect might be better described as "perceptual" rather than "traditional" Proteus effect. Further examples concerning the manipulation of body perception can be found in the works of Turbyne et al. (2021) and Matamala-Gomez et al. (2021).

While virtual human embodiment is most common in fully immersive VR, where the user's physical body is replaced by a virtual one, employing it in AR, where the physical body remains visually perceptible (see Figure S5), opens up a new design space in general and in the realm of body perception particularly. However, Genay et al. (2021) noted in their literature review that virtual human embodiment in AR is far less explored than in VR and lacks a common understanding and classification of existing knowledge. In consequence, the authors proposed the avatarization continuum, which describes the different degrees of avatar embodiment across all XR applications based on Milgram's reality-virtuality continuum. The continuum ranges from simply having and seeing the physical body in the physical environment to fully embodying avatars in VR. The degree of avatarization increases by supplementing the physical body with virtual objects (e.g., jewelry or clothing), replacing or superimposing real body parts, or fully embodying avatars displayed in AR mirrors (see Figure S5, right). Hence, AR allows users to experience a virtual body or body parts while still being in a familiar physical environment, breaking down the visual isolation of the VE and enabling direct comparisons between virtual and physical bodies. In addition, AR also enables interactions between users and non-immersed persons, allowing therapists or advisers to meditate on the user's body perception more easily when needed. For further application examples, the reader is referred to Fiedler et al. (2023b).

Motivation and Research Question

The previous sections delved into the nature of VEs in XR, the integration of virtual humans into these VEs, and the benefits and effects that can arise from their utilization. The support of body perception through the application and embodiment of virtual humans has further been identified as a relevant application domain. Within this domain, virtual humans can serve as predefined stimuli to investigate human body perception under controlled settings (Thaler, 2019) or to work on body perception beyond what reality allows (Horne et al., 2020; Matamala-Gomez et al., 2021; Turbyne et al., 2021). While initial research on the use of virtual humans in this domain shows promising results, prior research also noted the widespread use of highly different implementations of applications across various system configurations by diverse individuals (Wolf et al., 2020). However, this heterogeneity has the potential to impact how virtual humans are perceived in their role as predefined stimuli within VEs, thus systematically thwarting the intentions of researchers or application designers. Consequently, it is imperative to thoroughly comprehend and consider existing influences. Therefore, this dissertation focuses on the fundamental research of factors that can influence the visual perception of virtual humans in VEs. The literature research presented below revealed that existing influences can be categorized into a taxonomy of individual-, system- and application-related factors. It further indicated that the potential factors may be interconnected across categories and might interact in both simple and complex ways. Based on these observations, this dissertation's research questions have been defined as follows.

Research Questions

1. What individual-, system-, and application-related factors influence the visual perception of virtual humans in virtual environments?
2. How do they act individually?
3. How do they interact with each other?

To address the research questions, the subsequent sections will identify, analyze, and categorize various potential factors influencing the perception of virtual humans in VEs based on existing literature. Subsequently, the identified research gaps will be explored in the empirical part of the dissertation. Finally, the joint results will be discussed collectively, and specific implications will be derived. Although the empirical work presented in the following chapters primarily focuses on the area of body perception, the technical advancements and findings derived are applicable beyond the specific context, contributing to a broader understanding of the perception of virtual humans in VEs.

Factors Influencing the Perception of Virtual Humans in Virtual Environments

The following section introduces and analyzes various related work concerning the taxonomy of individual-, system-, and application-related factors that can influence the perception of virtual humans in VEs. Individual-related factors encompass influences that shape the user's subjective appraisal of a perceived virtual human based on the user's appearance, attitudes, habits, concerns, and so on. System-related factors, on the other hand, concern the technical characteristics of an XR system being used and are closely tied to the previously presented factors defining the immersion of a system. Finally, application-related factors refer to design decisions and specific implementations of VEs that may impact the perception of virtual humans within those environments. However, it is worth noting that those factors can be interconnected across different categories and interact in simple and complex ways. As an example, Thaler et al. (2018a) investigated the perception of virtual humans' body weight and found that the user's individual body mass index (BMI), according to the World Health Organization (2000) calculated as $\text{BMI} = \frac{\text{Body Weight in kg}}{(\text{Body Height in m})^2}$, significantly impacts the estimation of a virtual human's body weight. However, the impact was only shown when the estimated virtual human was presented with a photorealistically personalized texture. While some factors can be clearly assigned to a single category, the majority relate to different categories when considering their interplay. For example, the appearance of a generic virtual human can be considered an application-related factor. However, its congruency with the appearance of a particular individual might significantly influence its perception. In the following, we delve into each of the three categories while considering potential interactions when possible and present works that relate to the perception of virtual humans in the defined application area of body perception when available. However, the presented works do not represent a conclusive and fully comprehensive list of factors based on a systematic literature review but rather an accumulation of factors that have shown relevance in the course of this dissertation.

Individual-Related Factors

When considering individual-related factors that influence the perception of virtual humans, it suggests differentiating between "traditional" and XR technology-related factors. Traditional factors refer to self-related influences known to affect how we perceive other human beings or ourselves in reality. These include interpersonal factors such as cultural and social norms or stereotypes that originate from social psychology (Bierhoff, 1989) and can also influence the perception of virtual humans. For instance, J. Lin et al. (2023) showed that a virtual human resembling a doctor, fulfilling a widely accepted stereotype with a high social value, is perceived as more trustworthy than a virtual human looking like a punk, associated with a stereotype of lower social value. However, although the conformity of virtual humans to our social values and norms or stereotypes can greatly impact their perception, they appear less relevant individual-related factors for the present dissertation, which is also reflected by the lack of prior work in the direction of body perception in XR. Additionally, working on body perception suggests using personalized virtual humans that foster the reflection on the user's own appearance or neutral virtual humans that allow focusing on the body and not on their social appearance (Horne et al., 2020).

Traditional individual-related factors linked to the user's physical body play a more substantial role in body perception. Here, it can be distinguished between factors that relate to the user's external appearance and those that relate to the mental attitude towards their body. The former includes factors such as the user's body shape, gender, or age. An example of the influence of body shape is the contraction bias (K. K. Cornelissen et al., 2015, 2016), which suggests that estimating the body weight of humans is most accurate around an estimator-dependent reference template of a body (often the estimator's body). The accuracy decreases as the BMI difference from this reference increases, resulting in an underestimation of heavier bodies and an overestimation of lighter bodies. This effect applies especially to individuals that show a pathological deviation from average weight, which is often accompanied by a distortion of body image and has been reported based on both underestimation (Maximova et al., 2008; Valtolina, 1998) or overestimation (Docteur et al., 2010; Mölbert et al., 2017b). Thaler et al. (2018a, 2018b) observed similar patterns in individuals estimating the body weight of virtual humans on an AR projector screen. Another example formulates Weber's law, which suggests that it becomes increasingly difficult to detect differences in body weight as the body's weight increases (K. K. Cornelissen et al., 2016). Research has further shown that body misperception can be subject to gender-specific differences, rendering females more susceptible (Connor-Greene, 1988; Hsu, 1989; Paeratakul et al., 2002). As for the influence of age, studies have shown that older individuals are less prone to bodily misperceptions (B. Park et al., 2019).

Various studies have examined the influence of the user's external appearance on SoE. Prior work showed that an objective congruence in the appearance between users and their avatars achieved by photorealistic personalized avatar reconstruction leads to a significant increase in VBO (Gorisse et al., 2019; Salagean et al., 2023; Waltemate et al., 2018). However, this could not be replicated when using less faithful personalized avatar reconstructions, highlighting the importance of photorealism in this realm (Ma & Pan, 2022). These findings align with the CaP model of Latoschik and Wienrich (2022), which suggests that SoE is driven by the congruence between the expectation of having our real body and the visual perception of seeing a virtual body. The model further expects that enriching the embodied representation with personalized top-down information enhances the congruence between what we expect to be our body and what we visually perceive, thereby increasing the plausibility of the embodiment. Concerning body weight perception, Thaler et al. (2018a) investigated the influence of individuals' BMI on body weight estimations of non-embodied personalized generic virtual humans. They found that BMI affected estimations only when participants were estimating a personalized virtual human. The authors speculated that self-identification with the virtual human, based on the perceived self-similarity through self-related cues, could be a potential reason for the observed effect. Interestingly, Wolf et al. (2020) found similar effects when estimating a generic embodied avatar's body weight, raising the question of whether embodiment also serves as a self-related cue that fosters self-identification, which will be addressed in Chapter 2 of this dissertation. Both Wolf et al. (2020) and Thaler et al. (2018a) suggest that the congruence in appearance and behavior between the user and the virtual human might lead to self-similarity and self-attribution, resulting in self-identification with the virtual human. Based on their results, both prior works discuss that moderation of the user's perception of the virtual human through self-identification, the "process of identifying a [virtual] representation as being oneself" (Gonzalez-Franco et al., 2020b, p. 1), might play an important role. However, the role of self-identification in virtual human perception and embodiment seems to be sparsely researched so far. While subjectively perceived similarity and identification with an avatar is certainly an individual-related factor, the concrete implementation of avatars is a matter of application design that will be further discussed in the section on application-related factors. In summary, it can be assumed that the interplay between an individual's appearance and the application-dependent design of avatars can play a major role in body perception-related applications. As a result, the influence of individuals' appearance on the empirical results has been considered through different measures in this work's empirical chapters.

Other traditional factors that may also influence the perception of virtual humans relate to mental attitudes towards the physical body. For example, previous work has shown that individuals' self-esteem (O'Dea, 2012) and concerns about their body shape (Kamaria et al., 2016) can significantly influence body perception through dissatisfaction or perceptual distortion. These factors may also extend to the perception of virtual humans, particularly when being personalized. However, when analyzing several psychometric factors, including self-esteem and body shape concerns, Thaler et al. (2018a) could not show any influence of the psychometric factors on the users' body size estimates of their virtual alter egos. It is further known from previous work that self-esteem can significantly influence the perception of attractiveness. For example, Kenealy et al. (1991) and Patzer (1995) revealed correlations between self-esteem and how individuals rate their physical attractiveness. This observation can reflect in the preference for a self-representation, as Gorisse et al. (2018) showed that users with high self-esteem prefer their personalized virtual alter ego as an avatar, while users with low self-esteem turn to generic virtual humans. J. Park (2018) further highlighted self-esteem as a determinant factor of emotional reactions when observing a personalized virtual human in VR. Finally, Dunn and Guadagno (2012) showed a significant influence of self-esteem on users' decisions during an avatar individualization process. However, dedicated research on the influence of self-related psychometric measures on the perception of virtual humans seems to be scarce. Consequently, they have been considered covariates in all empirical works of this dissertation.

It is important to mention that there might also be XR technology-specific individual-related factors that influence the perception of virtual humans to ensure comprehensiveness. These factors encompass various aspects, such as individual immersive tendencies (Witmer & Singer, 1998), susceptibility to simulator sickness (Tian et al., 2022), previous experience with XR technology (Sagnier et al., 2020), or general technology acceptance and affinity (Henrich et al., 2022). However, while these factors are known for their potential impact on the UX of XR experiences in general, there is a dearth of research investigating their specific influence on the perception of virtual humans.

System-Related Factors

The second category includes system-related factors concerning the differences in virtual humans' visual perception caused by the technical characteristics of a used XR system. These include the priorly introduced properties that also define the immersion of an XR system (e.g., display resolution, field of view, refresh rate, or luminosity and transparency of virtual objects). To infer these characteristics' influence on virtual humans' perception, it is worth considering device-specific sensory congruences based on the CaP model of Latoschik and Wienrich (2022). Within the model, a larger field of view or higher resolution is expected to lead to stronger device-specific sensory congruence with our real-world habits and expectations. This alignment, in turn, generates plausible spatial cues that facilitate a faithful perception of the presented content, including virtual humans. At the same time, incongruencies, for example, through a transparent or distorted presentation of virtual humans, might negatively impact their perception. Mal et al. (2022) have focused on the plausibility of virtual humans in VEs and define virtual human plausibility as the user's subjective impression regarding how suitable and believable a virtual human seems within the VE. The authors distinguish between appearance and behavioral plausibility, which derives from the congruent context-specific behavior of a virtual human, and the perceived match of the virtual human with the VE, which is shaped by a congruent presentation of the virtual human and the VE. While the appearance and behavioral plausibility can be considered influenced mainly by the application-related factors discussed later, system-related factors can be expected to influence the match to the virtual environment. For example, incongruencies between the rendering style of the VE and the virtual human when using different immersive XR displays could lead to an influence on the perception of virtual humans. However, this has yet to be confirmed by empirical work, and therefore, was investigated in Chapter 5 further.

Empirical investigations comparing the perception of virtual humans between systems with different characteristics seem very rare so far (Genay et al., 2021). This lack might be because the availability of high-quality consumer AR displays seems to lag behind the development of consumer VR displays. In detail, devices that support AR and VR, particularly suitable for such comparisons (Wienrich et al., 2021b), have only slowly become established since the release of the HTC Vive Pro (HTC, 2018a). In a narrow literature review, Wolf et al. (2020) investigated potential factors influencing virtual human perception in AR and VR technologies concerning body perception. However, they encountered limited and methodically divergent research on the topic, making it challenging to draw clear conclusions about the influence of different display types from the literature. In their subsequent evaluation, they compared the perception of embodied avatars between VR and OST AR using the mentioned HTC Vive Pro. They found no significant differences in SoE and body weight estimations between conditions. However, based on noticeable descriptive differences between conditions and a significant underestimation of the avatar's body weight in both conditions, they could not completely rule out an influence on body weight perception. The latter is in line with previous studies that reported a general tendency to underestimate body weight in virtual humans across different XR systems (Nimcharoen et al., 2018; Piryankova et al., 2014a; Thaler et al., 2018a, 2018b, 2019). In consequence, a potential bias of body weight perception between different immersive XR experiences has been further explored systematically in Chapter 4 and Chapter 5.

As indicated in the section on individual-related factors, the affective appraisal of virtual humans (i.e., their humanness, attractiveness, and eeriness) can also be considered relevant in body perception. However, while there seems to be no work comparing the affective appraisal of virtual humans between different immersive XR systems, comparisons between VR and desktop systems could not show any significant differences (Hepperle et al., 2022; D. Roth & Wienrich, 2018). To extend this knowledge, Chapter 5 investigates the influence of different immersive XR systems on affective appraisal.

For virtual human embodiment, Genay et al. (2021) proposed that the degree of body avatarization is influenced by the type of display used and its level of immersion, ultimately impacting SoE. For instance, a limited field of view might negatively affect the feeling of VBO by disrupting the continuity of the embodied experience, particularly when employing full-body embodiment. When using OST AR displays, the direct visual feedback of the real body movements might affect the agency. While there is no latency in the view of the real body, there will always be a certain latency for the virtual body (Waltemate et al., 2016), causing a discrepancy between observed real movements and the motion of the virtual body. Additionally, the simultaneous visualization of both the real and virtual bodies may trigger direct comparisons and potentially diminish the sense of VBO. For example, Škola and Liarokapis (2016) investigated VBO in response to real-world, AR, and VR conditions and found a significant difference between the AR and real-world conditions but not between AR and VR. Waltemate et al. (2018) demonstrated that the user's SoE is significantly higher when experiencing virtual human embodiment in HMD-based VR compared to a projector-based AR system. Since further empirical work in this regard is still sparse, the SoE between different immersive XR experiences has been compared in Chapter 4.

Some further works investigated the influence of single system characteristics on the perception of virtual humans. However, only a limited number have been thoroughly explored so far. For instance, Peck et al. (2022) explored the influence of display transparency on the perceived humanness of virtual humans in OST AR displays. They discovered that darker skin tones are perceived as less human due to higher relative transparency, which may lead to unintentional racial bias. Similarly, Wang et al. (2017) found that the partially transparent content in OST AR could cause depth perception issues that might adversely affect the perception of virtual humans. Although a comparison of different XR experiences based on XR systems having the same system characteristics or investigating the impact of particular characteristics on its own should be favored (Wienrich et al., 2021b), the vast heterogeneity of present systems seems to make further comparisons between several differently immersive XR systems (e.g., OST AR, VST AR, CAVE-like systems, and VR) still inevitable (Wolf et al., 2020). While system-related factors that might affect the perception of virtual humans are akin to the system characteristics that define the immersion of an XR system, it cannot be assumed that similarly immersive systems will also provide a similar perception. A comparable phenomenon can be observed for the distance compression effect, which describes a tendency of underestimation distances in XR-based VEs. Although various current consumer HMDs provide a similar level of immersion, the degree of distance compression can still vary significantly depending on the HMD. However, the specific system characteristics causing this effect could not be conclusively isolated to date (Kelly, 2022).

An XR system comprises not only the visual display but also other technical components that might influence the perception of virtual humans. For example, when animating virtual humans, the accuracy and fidelity of body tracking during animation can significantly impact the virtual humans' perceived humanness (J. C. Thompson et al., 2011) or SoE (Yun et al., 2023). Latency or jitter in an XR system, resulting from insufficient system performance or deficient implementation (Stauffert et al., 2018, 2020), can also affect SoE through a diminished sense of agency of the embodied virtual human (Waltemate et al., 2016). However, since these factors are not further investigated in this work, our empirical work has always ensured a smoothly running XR system, including body tracking with a sufficiently accurate pose, high frame rate, and low end-to-end latency (Song & Godøy, 2016).

Application-Related Factors

The last category of factors concerns the application's design and may offer application designers the greatest potential for influencing (or avoiding unintentionally influencing) the perception of virtual humans through a sophisticated application design targeting a specific use case while also considering individual-related needs and preferences and system-related limitations and biases. To identify relevant application-related factors, the list of factors potentially influencing body perception presented by Wolf et al. (2020) has been considered. It rendered the observation perspective on the virtual human (i.e., first and/or third person), the utilization of virtual human embodiment (i.e., embodiment or no embodiment), and the personalization of the virtual human's appearance (i.e., generic, individualized, or personalized) as relevant. Moreover, the systematic literature review on the visualization of virtual humans in XR conducted by Weidner et al. (2023b) additionally highlighted the virtual humans' visible body parts (i.e., hands only, hands and head, or full-body) and their rendering style (i.e., abstract, cartoon, or realistic) as relevant factors.

In general, a plausible virtual representation of the user's body is desirable when implementing virtual humans in the domain of body perception. Hence, when considering the CaP model of Latoschik and Wienrich (2022), assessing the interplay between the various application-related factors listed above seems necessary. Emphasis should be given to a coherent design of virtual humans in the application design, ideally resulting in a plausible perception of a virtual human according to the aforementioned categorization considering appearance and behavioral plausibility and match to the virtual environment as suggested by Mal et al. (2022). Initial empirical work supports assumptions of the two concepts concerning the context-specific assessment of virtual humans in VR experiences based on manipulation in the application design (Mal et al., 2023).

When developing XR applications containing virtual humans, one of the early considerations should be the virtual humans' style and how they can be generated. Weidner et al. (2023a) investigated the benefits of different rendering styles and noted in their literature review that a realistic rendering of virtual humans usually outperforms lower realistic styles, resulting in better UX and task performance but also a significantly higher SoE, especially VBO. Applying personalization, particularly through photorealism, has been shown to enhance SoE and self-identification with virtual humans (Fiedler et al., 2023a; Gorisse et al., 2019; Salagean et al., 2023; Waltemate et al., 2018). Weidner et al. (2023a) further elaborated on the role of visible body parts when showing virtual humans in VEs. They noted that the visualization of the full body increases the UX and is, in most cases, preferable to a reduced representation. However, they did not mention concrete effects on the perception of virtual humans. For applications dealing with body perception, the literature suggests working with fully visible photorealistically personalized virtual humans (Döllinger et al., 2019; Gaggioli et al., 2003; Horne et al., 2020; Turbyne et al., 2021), as users might relate them better to themselves. Empirical support comes from Thaler et al. (2018a) and Piryankova et al. (2014a), who examined the role of personalization in relation to body perception and highlighted a more accurate and self-referential assessment of body weight as benefits. Their use could also increase the plausibility and credibility of the overall experience (Latoschik & Wienrich, 2022) and support behavioral and perceptual adaptation processes (Wienrich et al., 2021a). To investigate this topic further, Chapter 1 examines the UX of personalized virtual humans in body perception in detail.

When using photorealistic virtual humans to reflect on the physical self, their evaluation on an affective emotional level, rather than a purely cognitive one, might become an essential factor (Castelfranchi, 2000). For example, observing our virtual alter ego moving around as embodied agent is incongruent with what we are used to and could lead to creepy or uncanny feelings. Such feelings towards virtual humans are not unknown, as they are often associated with the Uncanny Valley effect. The effect describes the phenomenon that virtual humans, approaching a high degree of humanness in appearance, are perceived as particularly uncanny before reaching a completely indistinguishable lifelike appearance (Mori, 1970; Mori et al., 2012). The perceived uncanniness results from a function of its humanness and its affinity to the observer. It can be influenced by various manipulations, such as anthropomorphism (Chaminade et al., 2007; Lugrin et al., 2015) or stylism (Hepperle et al., 2020, 2022). However, uncanniness might also occur due to an unsatisfactory reconstruction of the own appearance (Bartl et al., 2021b). The reader is referred to Diel et al. (2021) for a comprehensive overview. To investigate the affective appraisal of virtual humans in the direction of body perception, the concept has been considered in Chapter 1, Chapter 3, and Chapter 5.

Another application-related factor that might influence the perception of virtual humans is the observer's visual perspective on a virtual human. Usually, it can be distinguished between an egocentric and allocentric perspective (Debarba et al., 2015). The egocentric perspective is based on the first-person perspective of the observer and offers only a limited view of the body, similar to how humans perceive their own physical bodies visually. In contrast, the allocentric perspective presents a more comprehensive view of the body from a third-person perspective, such as looking at oneself in a (virtual) mirror (Inoue & Kitazaki, 2021) or having an out-of-body experience (Bourdin et al., 2017). Concerning virtual human embodiment, various research has investigated how the visual observation perspective impacts SoE. For the supposedly bottom-up driven senses of agency and self-location, it can be assumed that only having the first-person or both perspectives together yields similar results. Gorisse et al. (2017) found that the sense of agency remains consistent when receiving visuomotor feedback from either first-person or third-person perspectives. Moreover, Debarba et al. (2017) showed that the observation perspective does not significantly impact agency unless the embodiment has multisensory inconsistencies. For self-location, the study results from Gorisse et al. (2017) indicate that the feeling is predominantly determined by the first-person perspective and only decreases when an avatar is exclusively embodied from a third-person perspective. However, the third-person perspective might become more relevant for the likewise top-down influenced feeling of VBO. Some prior works expect VBO to rise when a user receives a third-person perspective on an embodied avatar, as the holistic view of the body, including the face, is expected to provide potential cues for self-identification (Inoue & Kitazaki, 2021; Spanlang et al., 2014; Tsakiris, 2008). However, recent empirical works in the domains of body awareness (Döllinger et al., 2023b) or physical exercising (Bartl et al., 2022) question this assumption as they showed no effect of providing a virtual mirror on any dimension of SoE. In addition, Mottelson et al. (2023) analyzed over 50 studies investigating the effects of virtual human embodiment on SoE, of which about half used a mirror. Interestingly, the works without virtual mirrors reported larger effects on SoE than studies using virtual mirrors, suggesting that mirrors may even harm VBO. No difference could be shown in the feeling of agency. However, the authors point to a purely correlative observation based on a diverse body of work also involving generic virtual humans and speculate in this context that mirrors reduce VBO only by making the facial region appear incoherent with the user's face. On the other hand, the already described increase in VBO through personalization can only be accomplished by providing a third-person perspective, as users would otherwise not be aware of their virtual appearance at all, especially in the face area. Therefore, it can be assumed that the role of the observation perspective depends on the use case and the type of avatars used.

Applications utilizing virtual humans to enhance body perception often prioritize providing a third-person perspective (Thaler et al., 2019), as it is considered crucial for enabling users to reflect their physical appearance visually and to exploit the above-described advantages of photorealistically personalized virtual humans. Providing a third-person perspective is also known from real-world body image interventions, where exposure to the physical body through a mirror can be an essential part of the treatment strategy (Delinsky & Wilson, 2006; Griffen et al., 2018). Neyret et al. (2020a) compared the impact of the embodied perspective on body perception between a first-person and a third-person perspective. They found that having only a third-person perspective allowed the participants to perceive virtual humans more neutrally without negative biases, leading to a more attractive evaluation of the presented virtual humans. Unfortunately, they did not capture numeric estimates of the virtual human's body weight or analyze the influence of the participant's appearance. Thaler et al. (2019) conducted a study investigating the influence of first- and third-person perspectives on the perception of body weight and body part dimensions without inducing virtual human embodiment. Their study showed a significant effect of the perspective on the perception of body weight with more accurate estimates when estimating in a third-person perspective. P. L. Cornelissen et al. (2018) further noted in their work on image-based body mass judgments that providing a holistic picture of a body is crucial for estimating body weight accurately. However, when observing virtual humans allocentrically, the visual observation distance to the virtual human might influence their perception. For instance, the distance compression effect could lead to a misinterpretation of a virtual human's body size, as the distance-size relationships learned in reality may not be transferable to a compressed perception in XR (Kelly et al., 2018). Furthermore, a limited resolution in current HMDs might hinder the accurate perception of virtual humans' body shape at certain distances. Both potential effects can be considered as combinations of system- and application-related factors, which have not yet been systematically examined. Therefore, the influence of self-observation distance (SOD) will be explored in Chapter 3 of this work.

While there is already a lot of research on the effect of different observation perspectives on the perception of virtual humans concerning body perception, the influence of a virtual human embodiment as a factor itself seems to be less researched in this domain. Although the embodiment of virtual humans often entails a shift of the observation perspective on the virtual human, it is usually also accompanied by the induction of further sensory contingencies (Kilteni et al., 2012) that can also lead to an increased self-identification with a virtual human (Fiedler et al., 2023a). As reported earlier, Wolf et al. (2020) observed that the users' BMI moderated the users' body weight estimates of an embodied generic avatar in all of their conditions. Thaler et al. (2018a) previously observed a similar effect for body weight estimates of personalized virtual humans but without employing virtual human embodiment. In both papers, the question was raised whether this effect was due to increased self-identification either caused by embodiment or personalization with the virtual human, respectively. However, to our knowledge, this has not been investigated further so far. In the supposedly only study that explored the impact of embodiment on virtual human perception concerning body perception, S. Jung and Hughes (2016) showed that changes in the body shape of virtual humans are less well perceived when embodied to it. Consequently, the role of embodiment on the perception of virtual humans is investigated further in Chapter 2.

Chapter Overview

The previous sections introduced a taxonomy of individual-, system- and application-related factors that can influence the perception of virtual humans in VEs. Where available, prior work was presented that elaborated on the different factors assigned to each category. While some factors have a solid knowledge base, others appear less well-researched. The present dissertation comprises five chapters that explicitly investigate the previously identified research gaps. All works have been published in peer-reviewed journals (Chapter 1 and Chapter 3) or proceedings of international conferences (Chapter 2, Chapter 4, and Chapter 5) listed below in detail. The following sections provide an overview of each chapter, highlighting their objective, technical contribution, evaluation methodology, and outcomes. A copyright statement and a definition of the contributions of the publications' authors can be found at the end of each chapter. The author of this dissertation contributed to an additional 22 works that studied either different aspects of XR experiences in general or the role of virtual humans in such experiences. As they did not contribute directly to the present dissertation's topic, they have been added to the list of achievements in the appendices.

Chapters

Chapter 1: Döllinger, N., Wolf, E., Mal, D., Wenninger, S., Botsch, M., Latoschik, M. E., & Wienrich, C. (2022c). Resize me! Exploring the user experience of embodied realistic modulatable avatars for body image intervention in virtual reality. *Frontiers in Virtual Reality*, *3*. https://doi.org/10.3389/frvir.2022.935449

Chapter 2: Wolf, E., Merdan, N., Döllinger, N., Mal, D., Wienrich, C., Botsch, M., & Latoschik, M. E. (2021). The embodiment of photorealistic avatars influences female body weight perception in virtual reality. *2021 IEEE Virtual Reality and 3D User Interfaces (VR)*, 65–74. https://doi.org/10.1109/VR50410.2021.00027

Chapter 3: Wolf, E., Döllinger, N., Mal, D., Wenninger, S., Andrea, B., Botsch, M., Latoschik, M. E., & Wienrich, C. (2022a). Does distance matter? Embodiment and perception of personalized avatars in relation to the self-observation distance in virtual reality. *Frontiers in Virtual Reality*, *3*. https://doi.org/10.3389/frvir.2022.1031093

Chapter 4: Wolf, E., Fiedler, M. L., Döllinger, N., Wienrich, C., & Latoschik, M. E. (2022b). Exploring presence, avatar embodiment, and body perception with a holographic augmented reality mirror. *2022 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, 350–359. https://doi.org/10.1109/VR51125.2022.00054

Chapter 5: Wolf, E., Mal, D., Frohnapfel, V., Döllinger, N., Wenninger, S., Botsch, M., Latoschik, M. E., & Wienrich, C. (2022c). Plausibility and perception of personalized virtual humans between virtual and augmented reality. *2022 IEEE International Symposium on Mixed and Augmented Reality (ISMAR)*, 489–498. https://doi.org/10.1109/ISMAR55827.2022.00065

Chapter 1: Exploring the User Experience of Embodied Realistic Modulatable Avatars for Body Image Intervention in Virtual Reality

Objective

The work presented in Chapter 1 aimed to develop and evaluate a high-fidelity prototype of an advanced VR system that enables users to embody a rapidly generated photorealistically personalized avatar and to adjust its body weight realistically in real-time. The system was developed as part of the priorly mentioned ViTraS research project (Döllinger et al., 2019) with the goal of exploring new approaches to support body perception through body image interventions. Additionally, the system implementation was intended to research the factors that influence the perception of virtual humans in VEs as part of this dissertation. Hence, the presented system was used in different versions in the subsequent chapters to investigate their respective research questions. The conducted evaluation aimed to investigate the feeling of safety, physical comfort, and accessibility of the system, as well as measures of the VR-specific UX and usability relevant for the use in the area of body perception. It further explored basic measures capturing the perception of virtual humans and interaction methods relevant to the following chapters.

Technical Contribution

The implemented technical system enables the generation of photorealistically personalized virtual humans using a body scanning process based on the work of Achenbach et al. (2017) and their seamless integration into VEs at runtime. By extending the system architecture of Wolf et al. (2020), the virtual human can be displayed within a VE using any SteamVR (Valve, 2021) compatible XR display and real-time animated based on the user's body movements captured by SteamVR compatible consumer tracking devices using a inverse kinematic (IK)-based reconstruction (Aristidou et al., 2018) of the user's body pose. This approach allows virtual human embodiment from a first-person perspective and self-observation from a third-person perspective using a virtual mirror. The system further implements three different novel interaction techniques to modify the virtual human's body weight according to an enhanced version of the statistical model of weight gain/loss of Piryankova et al. (2014a).

Evaluation

The system has been evaluated using a mixed-method approach with a small sample of 12 healthy participants, including semi-structured qualitative interviews and multiple quantitative measures. It employed a 3×1 within-subjects design to compare three different body weight modification interaction methods using either joystick, gestures, or virtual objects. Participants embodied their avatars, generated through a body scan, in a VE during a VR exposure and had to perform different body movement tasks as well as an active modification task (AMT) and a passive estimation task (PET) on their avatar's body weight. The qualitative interviews evaluated the body scan, the assessment of body measures, and the VR exposure. Participants reported their expectations and feelings, their physical and psychological comfort, the perceived transparency of the process, their feelings about body weight modification and estimation, and their preferred interaction technique. The quantitative variables captured the feeling of presence and embodiment, indicators for simulator sickness, affective appraisal of the avatar's humanness, eeriness, and attractiveness, the perceived workload for the system calibration and the interaction methods, preferences for interaction methods, mean calibration and body weight modification times, and the results of body weight estimations captured either verbally using the PET or by avatar modification using the AMT.

Outcomes

The findings of Chapter 1 showed that the body scan experience was perceived as simple and interesting, with high acceptance and willingness to be scanned again. However, some participants felt watched and left alone during the process. Changes to the arrangement of cameras, as suggested by Wenninger et al. (2020) and evaluated by Bartl et al. (2021b), or a constant dialogue during the scanning process could reduce these negative feelings. The preparation and calibration for the VR experience were received positively, with low calibration times and workload ratings. Participants rated their perceived SoP on an acceptable level but with lower absolute ratings on involvement and realism as in comparable prior work (Buttussi & Chittaro, 2018; Wolf et al., 2020). The findings revealed similar for SoE, as participants rated VBO lower than comparable work (Waltemate et al., 2018, Chapter 2). Both might be attributed to the performed body weight modifications. Another reason could be inaccuracies in avatar generation combined with the body-related tasks, as many participants reported that their avatars were uncanny or not (entirely) recognizable as themselves. This finding raised the question of whether highly photorealistic personalization is currently necessary and feasible. The avatar's body weight modifications were generally well-received, but the lack of adjustments for specific body parts, as realized in other works (Maalin et al., 2020; Pujades et al., 2019), was seen as a limitation. Results also showed that modification via controller gestures or joystick is suitable for future work, with no difference in body weight estimation accuracy between methods. However, the PET provided significantly more accurate estimates than the AMT. In line with prior work (K. K. Cornelissen et al., 2015, 2016; Thaler et al., 2018a; Wolf et al., 2020), the accuracy of the body weight estimations depended on the presented avatar's body weight, with avatars heavier than the reference being underestimated and lighter ones even more pronounced being overestimated. High deviations and uncertainties in the estimations were generally observed and confirmed by qualitative feedback on task difficulty. The evaluation results were used to derive design guidelines for the body scanning process, application design, and body weight modification and estimation methods to guide future development and evaluation of systems supporting body perception. They are further considered in the subsequent chapters, except for Chapter 2, which has been completed earlier.

Chapter 2: The Embodiment of Photorealistic Avatars Influences Female Body Weight Perception in Virtual Reality

Objective

The work presented in Chapter 2 aimed to investigate whether the application-related factor of embodying a virtual human influences how this virtual human's body weight is perceived. Prior work suggested that embodying virtual humans with thinner or larger virtual bodies can alter the users' perception of their own body size (Keizer et al., 2016; Normand et al., 2011; Piryankova et al., 2014b). However, previous research also suggests that the users' body dimensions can similarly impact how they perceive virtual humans. Thaler et al. (2018a) found that the perceived body weight of a virtual human in a VE was predicted by the BMI of estimating users, but only when a virtual human's appearance was photorealistically personalized to them. Interestingly, Wolf et al. (2020) observed a similar effect for users being embodied to a non-personalized virtual human, leading to the question of whether the embodiment leads to a similar effect as personalization. Hence, the work's purpose was to confirm this observation while keeping the virtual human's appearance constant. It further aimed to confirm prior findings that virtual human embodiment considerably impacts the user's SoP (S. Jung & Hughes, 2016; Waltemate et al., 2018).

Technical Contribution

The technical system presented by Wolf et al. (2020) has been utilized to realize the VR embodiment condition and adapted to implement a control condition without embodiment. To this end, the existing IK-based avatar animation system has been extended to support the recording and playback of animation sequences in order to realize an autonomous moving agent in the condition without embodiment. The solution has been incorporated into the system presented in Chapter 1 as part of the described development process and was further employed in Chapter 5.

Evaluation

To investigate the impact of virtual human embodiment on body weight perception and SoP, the performed evaluation employed a 2×1 between-subject design. In the original embodiment condition of Wolf et al. (2020), a group of 26 female participants embodied a non-personalized (generic) virtual human and performed five visuomotor tasks while observing their movements reflected in a virtual mirror. In the additional "no embodiment" condition, 26 additional participants passively observed the same virtual human performing the same body movements (controlled by prerecorded animations) as in the embodiment condition. However, the virtual human was located in an adjacent room and observed through a door frame instead of a virtual mirror. Therefore, the virtual human could be observed from the same third-person perspective in both conditions, while the first-person perspective was only available in the embodiment condition. After the tasks, participants were asked for body weight estimations of the virtual human and their perceived SoP and SoE. The latter one was used to check for a successful manipulation. Furthermore, indicators for simulator sickness, body shape concerns, self-esteem, and the participant's BMI have been captured as individual-related factors for control purposes.

Outcomes

The results on SoE confirmed a successful manipulation between the embodiment and the no embodiment condition, with significantly higher SoE scores reported in the embodiment condition. The outcomes for body weight perception showed that the body weight of a non-personalized virtual human could be estimated accurately without embodiment. However, there was a significant bias towards an underestimation when the virtual human was embodied. The presence or absence of virtual human embodiment further moderated the relationship between the participant's BMI and the body weight estimations of the virtual human significantly, revealing a significant prediction of the body weight estimations in the embodiment condition but not in the no embodiment condition. A negative BMI difference between the participants' BMI and the virtual humans' BMI led to an underestimation of the virtual human, while a positive led to an overestimation. The results suggest that embodiment can influence body weight perception similarly to personalization (Thaler et al., 2018a), which could highlight the induced self-identification with a virtual human as a relevant factor. However, this assumption needs further confirmation, as discussed later in this dissertation. The results of the SoP measures confirmed previous findings that virtual human embodiment leads to a higher SoP (S. Jung & Hughes, 2016; Waltemate et al., 2018). Finally, no significant mediating effect of SoP, VBO, and agency on the relationship between condition and body weight perception nor further significant influences of the control measures on the dependent variables could be found. In summary, the results showed that the embodiment of virtual humans can significantly impact their body weight perception.

Chapter 3: Embodiment and Perception of Personalized Avatars in Relation to the Self-Observation Distance in Virtual Reality

Objective

The aim of the work presented in Chapter 3 was to investigate the effects of the visual SOD on the perception of embodied avatars in VR. SOD refers to the distance between the user-embodied avatar and a virtual mirror that provides the user with a holistic third-person observation perspective on their virtual body (Debarba et al., 2015; Inoue & Kitazaki, 2021) and can therefore be considered an application-related factor. However, the extent of a possible effect is also likely to depend on system-related factors, such as the rendering resolution or the distance compression effect. Previous work has shown that those distance-related biases can significantly affect the user's perception of VEs (Kelly, 2022; Renner et al., 2013). Additionally, the results of Chapter 4 of this dissertation left room for speculation about whether those biases could cause differences in the perception of virtual humans. Hence, the chapter's purpose was to investigate these observations, uncover unintended effects of uncontrolled SODs, and contribute to understanding how distance-related biases affect perception in VEs.

Technical Contribution

The work in Chapter 3 mainly employed the technical system described in Chapter 1 to realize the VR experience, including virtual human embodiment and body weight modifications. However, for better control of the SOD, the system was extended by an automatic spatial calibration, which aligns the virtual environment to the real environment using the Kabsch algorithm (Müller et al., 2016). To this end, the positions of the SteamVR Base Stations have been utilized as corresponding reference points in both environments. By operating this approach, it was possible to ensure that participants always faced the correct SOD after repeated entry into the VE while remaining in the same spot in the real environment.

Evaluation

In a 3×1 within-subject design, the distance between the photorealistically personalized user-embodied avatar and the virtual mirror has been systematically manipulated between a short (1 m), middle (2.5 m), and far (4 m) distance. A total of 30 participants performed body movement and body weight estimation tasks in each condition in front of the virtual mirror within a carefully controlled VE. The body weight estimation tasks included an AMT, where participants had to modify their avatar's body weight to their current, ideal, and the society's guessed average body weight, and a PET, where they had to estimate the avatar's passively modified body weight repeatedly. The manipulation got verified by asking participants to estimate the distance to the virtual mirror, which was also used to calculate the perceived distance compression (Philbeck & Loomis, 1997). After the VR exposure, participants answered questions about their SoE and self-identification towards the virtual human and its affective appraisal concerning humanness, eeriness, and attractiveness. Additionally, indicators for simulator sickness and the participants' body shape concerns and self-esteem have been controlled as individual-related factors.

Outcomes

The results on distance estimations confirmed a successful manipulation between the different SODs and a significant distance compression effect. However, the observed compression averaged around 12 % , which is relatively small compared to other state-of-the-art consumer

HMDs (Buck et al., 2018; Kelly, 2022; Kelly et al., 2022). The reason could be a compensating effect of the provided first-person perspective on the embodied avatar (Gonzalez-Franco et al., 2019; Leyrer et al., 2011; Mohler et al., 2010). For the participants' SoE and self-identification towards their avatar, the results showed no significant differences between the SODs. The findings align with previous research on the SoE subdimensions of agency and self-location (Debarba et al., 2017; Gorisse et al., 2017; Inoue & Kitazaki, 2021; Kilteni et al., 2012). However, they contradict the assumptions for the subdimensions of VBO, self-similarity, and self-attribution. The body weight perception results showed no significant difference in the participant's body weight estimations for none of the captured measures. However, estimations were perceived as more difficult at the widest SOD. Concerning the controls, the participants' self-esteem and body shape concerns significantly predicted the estimation of their current body weight and their perceived body weight estimation difficulty, which aligns with assumptions of prior work (Irvine et al., 2019; Kamaria et al., 2016; O'Dea, 2012). In addition, the study revealed no significant differences in participants' affective appraisal of their personalized avatars between the SODs. However, the assessment of the controls showed that the participants' self-esteem predicted the avatar's perceived attractiveness and that their body shape concerns predicted the avatar's perceived eeriness. A design guideline for practical application could be derived from the findings, stating that the SOD can be freely chosen within the tested range of one to four meters without expecting major influences on the perception of the avatar.

Chapter 4: Exploring Presence, Avatar Embodiment, and Body Perception with a Holographic Augmented Reality Mirror

Objective

The work presented in Chapter 4 aimed to extend the VR embodiment system presented in Chapter 1 by integrating an OST AR display that allows users to interact with their self-embodied avatar in a holographic AR mirror without needing additional body-tracking devices. It expands the so far limited research on AR embodiment systems (Genay et al., 2021) and explores its potential benefits, particularly in the context of body perception. AR embodiment systems might offer unique benefits by incorporating real elements into an experience, such as the user's physical body or a therapist located in the real environment. The work further aimed to compare the developed system to the potentially higher immersive VR and VST AR systems presented by Wolf et al. (2020) in terms of the potentially relevant treatment effect mediators SoP, SoE, and body weight perception (Wienrich et al., 2021a).

Hence, the purpose of the present work was to contribute to the research of system-related factors influencing the perception of virtual humans and to gain a deeper understanding of the potential advantages and disadvantages of different AR and VR embodiment systems.

Technical Contribution

To realize the holographic AR mirror, the work extended the avatar embodiment system presented in Chapter 1 by a Microsoft HoloLens 2 OST AR HMD (Microsoft, 2019a). For this reason, Microsoft's Mixed Reality Toolkit 2 (Microsoft, 2019b) has been integrated into the system. The work further substituted the VR hardware-based body tracking system and integrated the markerless outside-in full-body tracking system from Captury (Captury, 2021; Stoll et al., 2011). Since both systems work in different coordinate systems, a customized solution has been implemented to link the captured body pose to the current position of the HMD without causing typical artifacts like sliding feet when moving the head. To overcome the tracking system's limitations regarding hand tracking quality, the markerless inside-out hand tracking provided by the OST AR HMD has been integrated into the embodiment system, allowing for a seamless switch between the two tracking systems whenever a user's hand entered or exited the HMD's tracking area. The developed solution allows users to experience a fully animated embodied avatar in a holographic AR mirror displayed on a wall in front of them simply by wearing the HMD within the body tracking system's coverage area.

Evaluation

The system has been evaluated through a user study involving 27 normal-weight female participants and following the procedure presented by Wolf et al. (2020). Participants provided qualitative feedback on the perception of the photorealistic generic avatar's appearance and movements, the HMD's display properties, and the body tracking accuracy. Additionally, their SoP, SoE, and body weight estimations have been captured. To classify the performance of the holographic AR mirror system, the collected data has been compared in a 3×1 between-subject design with data from prior work on VST AR and VR systems (Wolf et al., 2020). Self-esteem, body shape concerns, simulator sickness, and the participant's BMI have been captured as potential individual-related confounds.

Outcomes

The results of the qualitative interviews in Chapter 4 provided positive feedback regarding the holographic AR mirror, especially highlighting the quick and easy setup and the solid implementation. However, the analysis also revealed potential improvements, particularly concerning the used HMD's field of view, the mirror's brightness and transparency in physical space, the lack of avatar animations (i.e., eye, face, finger movements), and the fidelity of the embodied avatar's pose. Comparing the quantitative findings to the display conditions of Wolf et al. (2020), participants using the OST AR display reported the significantly lowest SoP. The results can be attributed to the potentially lower immersion of the used OST AR display and the lower plausibility of the conveyed OST AR experience (Latoschik & Wienrich, 2022; Skarbez et al., 2021b) and are in line with prior work (Chicchi Giglioli et al., 2019; Cummings & Bailenson, 2016; Waltemate et al., 2018). Surprisingly, no significant differences between the OST AR system and the VST AR and VR systems for SoE (VBO and agency) could be observed, suggesting that OST AR avatar embodiment systems can provide a convincing VBO despite potential shortcomings in immersion and plausibility. Additionally, the results indicate that agency is robust despite the relatively high latency of markerless body tracking and the presence of the participant's physical body next to the mirror image, as already observed in prior work (Latoschik et al., 2016). Significant differences in body weight estimations between the OST AR display and the VST AR display used by Wolf et al. (2020) have been revealed regarding body weight perception. For example, a female avatar with 68 kg would have been estimated at 63.29 kg on average when observed by the VST AR display and 69.07 kg when using the OST AR display. The findings demonstrate that display technology can significantly impact body weight perception and confirm the assumptions already made by Wolf et al. (2020). The study did not further confirm the previous observations that participants' BMI influences body weight estimates, raising further questions about the impact of display technology on body weight perception and the interplay with other factors. The results of the control variables showed neither group differences nor influences on the dependent variables. In summary, the work expands avatar embodiment systems towards OST AR display technology and provides initial comparative insights to comparable VST AR and VR systems.

Chapter 5: Plausibility and Perception of Personalized Virtual Humans between Virtual and Augmented Reality

Objective

The work presented in Chapter 5 aimed to investigate the system-related impact of different immersive and congruent XR experiences realized by VR, VST AR, and OST AR displays on users' general XR experience and their perception and plausibility of personalized virtual humans. When using virtual humans to support body perception in XR, an accurate and plausible perception of the virtual humans and a high overall quality of XR experience can be beneficial to achieve desired effects (Turbyne et al., 2021; Wienrich et al., 2021a). However, theoretical models (Latoschik & Wienrich, 2022; Skarbez et al., 2017, 2021b; Wienrich et al., 2021b) and prior research (Chapter 4, Chicchi Giglioli et al., 2019; Cummings & Bailenson, 2016; Waltemate et al., 2018; Wolf et al., 2020) suggest that the type of the XR display used impacts the SoP and plausibility of an XR experience as well as the perception of virtual humans (i.e., body weight perception, humanness, attractiveness, eeriness). Hence, this chapter aimed to confirm assumptions regarding the XR display's impact on the general XR experience made by recent theoretical models and to investigate priorly observed differences in the perception of virtual humans between different VEs in a controlled user study.

Technical Contribution

The technical system utilized the VR and VST AR experience using a Varjo XR-3 HMD (Varjo, 2021b). To this end, the implementation described in Chapter 1 has been extended by the Varjo Base 3 interface (Varjo, 2021a). In this process, a seamless transformation between AR and VR experiences during runtime has been introduced, automatically putting the relevant virtual objects in the scene on the correct rendering layers and allowing for their automatic spatial alignment in the real environment. The OST AR experience has been realized using a Microsoft HoloLens 2 (Microsoft, 2019a) and used the integration implemented in Chapter 4. The movement animation recording was performed using the animation system introduced in Chapter 2. However, an advanced playback system was implemented to realize the reappearance of the virtual human with a modified body weight, paying distinct attention to avoiding collisions between the virtual human's body shape and the animated arm positions, particularly when the body weight has been increased. The body weight modification followed the implementation introduced in Chapter 1.

Evaluation

For the user evaluation, the devices' provided degree of immersion has first been classified based on their hardware specifications (Skarbez et al., 2021b; Slater, 2009), while the device-specific congruences and incongruences of the XR experiences have been determined according to the CaP model (Latoschik & Wienrich, 2022). The performed study employed a counterbalanced 3×1 within-subject design, where 42 participants sat calmly on a chair in a laboratory and observed a photorealistic reconstructed virtual alter ego personalized to their appearance entering the laboratory, posing, and leaving several times. For each recurrence, the virtual human's body weight was passively modified, and the participants were asked to estimate it verbally (PET). After the experience, participants had to judge the spatial presence felt during the XR experience and rate the virtual human regarding its plausibility, humanness, eeriness, and attractiveness. The occurrence of simulator sickness-related symptoms has also been monitored since VST AR experiences can be particularly susceptible to simulator sickness due to the delay between video see-through recording and rendering it as the environment.

Outcomes

The findings for SoP and virtual human plausibility support the performed classification of the displays' degree of immersion and the congruences and incongruences of the XR experiences' offered content. Hence, the results are consistent with the theoretical assumptions of the CaP model (Latoschik & Wienrich, 2022) and align with the recently introduced taxonomy for describing XR experiences by Skarbez et al. (2021b). As expected, the potentially more immersive XR-3 (VR, VST AR) led to a significantly higher spatial presence compared to the HoloLens 2 (OST AR). Moreover, the more congruent VR experience led to a significantly higher perceived virtual human plausibility concerning the match to the environment compared to the AR experiences. In contrast, the virtual human's appearance and behavior plausibility was not affected by the AR experiences' incongruence of having a rendered virtual human within a real environment. In line with the results of Chapter 4, significant differences between VR and VST AR (XR-3) compared to OST AR (HoloLens 2) for body weight estimations could be shown. This suggests that a device's degree immersion, or rather one or more of the device-specific hardware characteristics, seems to be the main factor affecting the body weight perception of virtual humans. When analyzing the influence of the degree of body weight modification of the virtual human (i.e., the body weight difference between the virtual human and its observer), Weber's law (K. K. Cornelissen et al., 2016) could be confirmed, showing that body weight estimations become significantly more difficult with higher absolute estimation deviations when increasing modification levels. An exploration of gender differences showed no significant impact on body weight estimations. The results of the virtual humans' affective appraisal suggest that differences in immersion and congruence between XR experiences are unlikely to affect humanness, attractiveness, and eeriness, as no significant differences between conditions have been found. In conclusion, the study confirmed recent theoretical models describing XR experiences and provided valuable insights into the effects of display types on body weight perception. Additionally, using body weight estimations as a performance-based objective metric measure to determine display-related differences concerning the perception of virtual humans offers a nuanced perspective beyond highly subjective item-based questionnaires usually used in the field.

General Discussion

Virtual humans often play a central role in XR applications and can significantly shape the user's UX. However, especially in serious XR applications, where virtual humans can be used to induce behavioral, attitudinal, or perceptual changes, the correct perception of virtual humans according to the intended change effort is crucial. In this regard, applications for supporting body perception serve as this dissertation's primary exemplary use case. The initial literature review highlighted multiple factors influencing the perception of virtual humans in VEs, which have been divided into a taxonomy consisting of individual-, system-, and application-related factors. Our proposed research question focuses on understanding how these factors influence the user's perception of virtual humans in VEs, both individually and in combination with each other. To investigate this question, the present work comprises five empirical chapters, all based on high-ranked and peer-reviewed publications. However, throughout the dissertation period, the dissertation's author collaborated with different coauthors and conducted 22 additional supplementary works that indirectly contributed to exploring the research question. Various works and parts of the developed technical system have been disseminated online or in person by the dissertation's author at 12 national and international conferences. A comprehensive overview of publications, dissemination activities, and received awards can be found in the list of achievements in the appendices.

The following sections will discuss the outcomes of the five main chapters in light of the proposed research question. Whenever possible, knowledge gained from the additionally conducted works will be incorporated. To this end, the findings of the different chapters have been clustered into categories that highlight the results across studies and reflect on potential relationships between the different influencing factors. Finally, the technical contributions achieved across the different chapters will be summarized.

The Role of the Own Body and Attitudes About It

Across the presented empirical works, we examined several aspects of the influence of our participants' physical bodies and their attitudes about it on their perceptions of virtual humans in VEs. Chapter 1, Chapter 3, and Chapter 5 employed systematic body weight modifications, ranging between $\pm 20\,\%$ divided into $\pm 5\,\%$ intervals, to investigate how individuals perceive personalized virtual humans' body weight. Their findings consistently demonstrated that as the deviation between the virtual human's body weight and the participants' body weight increased, their accuracy in estimating body weight in both directions decreased. These results support the contraction bias theory assumptions (K. K. Cornelissen et al., 2015, 2016) and suggest that individuals use their own bodies as a reference template when estimating personalized virtual humans, resulting in more accurate estimates around their individual body weight. Notably, when investigating the influence of the participants' BMI on estimations of the generic embodied virtual human in Chapter 2, the most accurate estimations of the virtual human aligned with the average BMI for the tested population's age group ($M = 23.7$, Statistisches Bundesamt, 2021). This observation indicates that the implicitly applied reference template might change between estimating personalized and generic virtual humans.

However, the most surprising result from Chapter 2 was the significantly stronger pronounced contraction bias observed when estimating a generic virtual human as an embodied avatar than estimating it as an agent. This finding aligns with the assumptions of Wolf et al. (2020) and Thaler et al. (2018a), who proposed that an individual's body weight has a greater influence on estimating a virtual human's body weight when the individual can identify with the virtual human through its appearance (i.e., through personalization) or behavior (i.e., through embodiment). The observation could be further linked to the application of double standards, which describe the implicit use of different judgment criteria when judging more than one individual based on features such as gender or identity (Foschi, 1996; Voges et al., 2019). In this regard, Voges et al. (2022) have recently highlighted the apparent use of double standards in judging the own versus others' bodies in the context of body perception. However, our attempt to explain the variance in body weight estimates of personalized avatars through self-identification estimates in Chapter 3 yielded no significant results. A comprehensive evaluation of the influence of embodiment and personalization on body weight perception, including a potential moderation through subjective self-identification, could contribute to further clarification. The recently published study by Fiedler et al. (2023a), conducted in the context of this dissertation, investigated the influence of embodiment and personalization on self-identification using the same items for capturing self-identification as Chapter 3. Their results confirmed our observations and showed that embodiment and personalization each separately increased self-identification with a virtual human, complementing each other to attain the highest self-identification.

The results of Chapter 1, Chapter 3, and Chapter 5 consistently indicate further that the estimation of body weight becomes more difficult and inaccurate as the body weight of the virtual human decreases. This finding possibly contradicts the assumptions of Weber's law (K. K. Cornelissen et al., 2016) that body weight estimates are more difficult for higher body weight levels and suggests that even participants with average body weight are proportionately more insecure about estimating decreased body weight instead of increased.

Additionally, attitudes about the own physical body can play a significant role when perceiving virtual humans. Following the introduced literature, self-esteem and body shape concerns have been included as individual-related control variables in Chapter 2, Chapter 3, and Chapter 4. While both variables mainly controlled for possible group differences in the between-subjects designs in Chapter 2 and Chapter 4, significant influences could be shown on several measures in Chapter 3. Participants' self-esteem predicted the accuracy of their body weight estimation, with higher self-esteem associated with more accurate estimations. Additionally, both self-esteem and body shape concerns influenced the perceived difficulty of body weight estimations, with higher body shape concerns and lower self-esteem leading to greater perceived difficulty. These findings support previous research suggesting a link between self-esteem, body shape concerns, and body perception (Irvine et al., 2019; Kamaria et al., 2016; O'Dea, 2012). Furthermore, participants' self-esteem impacted the perceived attractiveness of their personalized embodied virtual humans, with higher self-esteem associated with a higher perceived attractiveness. This finding can be attributed to personalization, which seems to stimulate the well-known link between evaluating the own physical attractiveness (on the alter ego) and self-esteem (Kenealy et al., 1991; Patzer, 1995). Finally, body shape concerns were found to predict the perceived eeriness of the virtual human, with higher body shape concerns associated with lower perceived eeriness. This observation might be due to the fact that participants focus their attention on features of the virtual human that represent their own body concerns rather than irregularly reconstructed areas (Bauer et al., 2017; Tuschen-Caffier et al., 2015). The results emphasize the importance of considering self-esteem and body shape concerns as covariates in studies investigating the perception of virtual humans in VEs beyond the body perception domain, mainly when using personalized virtual humans or between-subject designs. Further research is needed to fully understand the role of self-esteem and body concerns in the perception of virtual humans.

Discovering System-Induced Biases

Chapter 4 and Chapter 5 explored the influence of system-related factors on the perception of virtual humans. Chapter 4 compared participants' body weight perception between using a OST AR HMD (realized by the HoloLens 2, Microsoft, 2019a), a VST AR HMD, and a VR HMD (both realized by the Vive Pro, HTC, 2018a). The results showed that participants using the HoloLens 2 estimated the body weight of an embodied generic virtual human presented in a virtual mirror significantly higher compared to those using the Vive Pro. This finding confirmed the assumptions of Wolf et al. (2020) regarding the existence of a display-related bias in body weight perception for the first time. The observed bias has been

Figure S6: Exemplary visualization of the discovered display bias using the body weight modification method from Chapter 1 based on the body weight estimations obtained in Chapter 4. The left image shows the virtual human (initially weighing 100 kg) as perceived with the VST AR display (93 kg), while the right image shows it as perceived with the OST AR display (102 kg). The middle image highlights the divergence between both in red color.

exemplarily visualized in Figure S6. Interestingly, a further analysis considering the participant's BMI as a moderator between display conditions and body weight estimations yielded no significant results, suggesting that AR-based virtual human embodiment might not lead to a sufficient self-identification to evoke a significant prediction of the body weight estimations by the participant's BMI as reported in Chapter 2 and discussed above. However, since the results presented in Chapter 4 are based on the analysis using data from two comparable but not identical studies, another improved comparison was conducted in Chapter 5, using a holistic study design and a state-of-the-art VST AR and VR device. This comparison omitted the use of virtual human embodiment to minimize potential interindividual variance due to a moderation through the participants' body weight, as shown in Chapter 2 and Chapter 4. The results revealed significant differences in body weight perception between the Varjo XR-3 (Varjo, 2021b), used as VR and VST AR display, compared to the Microsoft HoloLens 2 (Microsoft, 2019a), used as an OST AR display. Hence, both studies only found significant differences between conditions using different devices (VST AR and VR vs. OST AR) but not between the AR and VR conditions. These findings suggest that the hardware-specific properties, also defining the immersion of a device (e.g., built-in lenses, field of view, resolution of the display and its luminosity, or transparency of the rendered content), act as the main moderator for the observed display bias in body weight perception. When comparing the results on body weight perception between all chapters descriptively, it is worth noting that the Valve Index (Valve, 2020c) provided the highest estimation fidelity across all tested AR and VR HMDs, closely followed by the Varjo XR-3. Using the Microsoft Hololens 2 and the HTC Vive Pro resulted in high body weight misestimations.

Another display-related perceptual distortion often associated with the hardware characteristics of an HMD is the distance compression effect (Kelly, 2022; Loomis & Knapp, 2003). Both Chapter 4 and Chapter 5 discussed whether the observed display-related bias in body weight perception could be related to distorted distance perception. For instance, while a significant difference in body weight perception between Varjo XR-3 and Microsoft HoloLens 2 has been observed in Chapter 5, Adams et al. (2022) also found a significant difference in distance perception between these two devices, raising the question whether both observed differences have similar causes. Therefore, Chapter 3 focused on investigating the influence of the SOD on body weight perception. However, a systematic variation of the SOD did not reveal differences in body weight perception. Additionally, the determined distance compression of the Valve Index HMD used turned out to be relatively low at an average of about 12 % compared to other devices (Kelly, 2022). The low distance compression effect aligns with the accurate results of the body weight perception tasks, where no significant differences from the ground truth could be observed. Altogether, the chapter's results clearly revealed the existence of a display bias influencing the body weight perception of virtual humans in VEs that needs to be addressed in the application design, as discussed below. However, it could not definitely be determined whether the observed display bias in body weight perception has similar causes as the effect of distance compression. Further investigations are needed to determine the underlying components leading to the observed distortion, ideally in conjunction with investigations on distance compression.

Implications for XR Application Design

The following sections discuss the results of the conducted empirical works regarding the investigated application-related factors influencing the perception of virtual humans in VEs. In conjunction with the discovered effects of individual and system-related factors mentioned earlier, further specific implications on the application design in the field of body perception and beyond will be derived. Understanding the impact of the interplay between individual-, system-, and application-related factors is crucial in comprehending the perception of virtual humans in VEs and can guide the design and development of XR systems to enhance UX.

Challenges in the Animation and Reconstruction of Virtual Humans

Chapter 1 explored the overall UX of embodied and realistically modifiable personalized virtual humans, starting from the body scanning and virtual human reconstruction process. Reports about the body scanning process revealed that participants generally had positive experiences, finding it simple and interesting to get scanned. However, some participants reported feeling observed or left alone during the process. Potential solutions could be adaptions in the camera arrangement and a continuous dialog about the process with the participants. Although the reconstruction process itself does not directly impact the perception of virtual humans within VEs, it can create expectations regarding the virtual humans' appearance that indirectly influences its perception. For example, results from Chapter 1 revealed that participants have generally high and critical expectations about the quality of their alter ego when photorealistically reconstructed, especially in hand and face areas. Furthermore, the qualitative outcomes from Chapter 1 and Chapter 4 clearly highlighted that participants were susceptible to reconstruction errors of the virtual humans, the lack of facial expressions, and the limited fidelity of their body pose during embodiment. These issues impacted the overall UX negatively and triggered feelings of alienation toward the virtual human to the point of describing it as uncanny or eerie. Chapter 3 showed that these feelings are mostly insensitive to a change in the SOD, which is surprising, as they had been expected to be reduced with poorer recognizability due to the proportionally reduced size and rendering resolution. Across all performed studies involving virtual human embodiment, constant informal qualitative feedback emphasized the importance of the virtual humans' hand representation, as these are most of the time in the user's direct field of view. Participants described non-personalized or not faithfully reconstructed hands as particularly distracting. These reports align with the recent review of Weidner et al. (2023a) on the visualization of virtual humans in XR, which even formulated a design guideline on the importance of realistic hands when performing hand interactions.

There are several possible solutions to the concerns mentioned above. To address reconstruction errors, a reduction of the degree of realism, primarily of the texture but also of the body shape, as suggested by Salagean et al. (2023) or Zell et al. (2015), can be considered. However, while Zell et al. (2015) highlighted that reducing realism could reduce uncanniness while maintaining attractiveness, Salagean et al. (2023) showed that reducing realism through stylization can negatively impact SoE and self-identification. Another alternative is to employ alternative reconstruction methods, such as the Virtual Caliper of Pujades et al. (2019), which only personalizes the generated virtual humans based on users' body shape. This approach could also reduce the lack of reconstruction accuracy in the facial area, which potentially occurs mainly when personalizing textures. The results raise general doubts about whether creating highly photorealistic textures for virtual humans is currently feasible without triggering negative or even harmful side effects. Concerning the implications for applications supporting body perception, Horne et al. (2020) emphasize the importance of personalization. However, no work has been found that investigates the impact of reducing the degree of realism of virtual humans on the outcomes of such applications.

There are several possible solutions for the feedback on the body pose of the virtual human, which has sometimes been described as not sufficiently faithfully reconstructed. However, none of these solutions come without drawbacks. Most of the here conducted work utilized IK-based approximation of the body pose (Aristidou et al., 2018), which did not always produce results precisely corresponding to users' body pose and movements due to the lack of tracking points (e.g., on elbows or knees). Chapter 4 opted for an external markerless tracking system from Captury (Captury, 2021; Stoll et al., 2011) that yielded a more faithful body pose but introduced additional delay to the pose animation due to computationally intensive pose calculation based on RGB camera input, also resulting in occasional jittering of the pose. Another alternative could be marker-based body tracking using systems such as those from OptiTrack (NaturalPoint, 2018). However, these systems are limited in the field of body perception due to their invasiveness, requiring participants to wear suits or attach numerous markers to their bodies. Recently, AI-based approaches for reconstructing body poses based on sparse provided tracking information, such as those proposed by Jiang et al. (2022), have attracted attention but are in early research stages. The use of these approaches will be further discussed in the section on incorporating technical advancements along with the use of advanced technologies to animate the face area of virtual humans.

Modification and Estimation of Body Weight on Virtual Humans

The perception of virtual humans concerning body perception has been operationalized using body weight estimates in combination with body weight modifications. To this end, a statistical model of weight gain/loss originally based on the work of Piryankova et al. (2014a) has been utilized. However, the computation of modifications in the facial region has been optimized as presented in Chapter 1. The in Chapter 1 performed evaluation revealed that real-time body weight modifications on an embodied virtual human could lead to a decline in SoE, as lower subjective ratings as in comparable work without body weight modifications have been observed (Waltemate et al., 2018; Wolf et al., 2020). Chapter 1 further explored different interaction methods to interactively modify the embodied virtual human's body weight. While the investigation found that the kind of interaction method used did not impact the perception of a virtual human's body weight, it showed that body weight modifications using the controller's joystick or by performing hand gestures have superior usability compared to the use of virtual objects as buttons. Another advantage of the modification via hand gestures is their simplicity, which does not necessarily require hardware-based controllers. Therefore, it can also be used with devices that only provide hand tracking, but no physical controllers, such as the recently announced Apple Vision Pro (Apple, 2022). Regardless of the interaction method, participants criticized the limited ability to modify specific body parts and body tissue compositions of virtual humans. This lack could be addressed by advanced modification methods, such as those presented by Maalin et al. (2020) or Pujades et al. (2019), which allow for more specific modifications beyond using only BMI as a single modification parameter. Furthermore, models simulating the anatomical body composition, such as that of Kadleček et al. (2016), could also be included in the body weight modification model.

Chapter 1 further introduced two different kinds of body weight estimation tasks for capturing participants' body weight perception. In the PET, participants had to numerically estimate the virtual human's body weight after the system had passively modified it. In the AMT, participants had to interactively change their virtual human's body weight to a given target weight. A comparison of both tasks revealed that the PET provided more accurate body weight estimates than the AMT. This difference could be attributed to the novelty of the AMT, as we are usually not used to modifying our own body weight while estimating it numerically is more common in everyday life. Both kinds of tasks followed the general pattern described by the contraction bias (K. K. Cornelissen et al., 2015, 2016). Since the PET provided the most accurate results, it has been used as the primary body weight estimation task throughout all chapters of this dissertation. Inspired by the works of Thaler et al. (2018a) and Neyret et al. (2020a), the AMT has been utilized in Chapter 3 to enable participants to adjust their embodied virtual alter ego's body weight to their own current and ideal body weight, both used to highlight perceptual differences between conditions but not to reflect on participant's individual body perception. Across all chapters and independent from the used estimation method, estimating body weight was qualitatively described as challenging, resulting in overall high interindividual quantitative deviations.

Considering Individual and System-Related Biases

Different individual- and system-related biases that can influence the perception of virtual humans in VEs have been discovered throughout this dissertation. These biases need to be considered when designing and developing applications containing virtual humans, particularly those supporting body perception. The section on the role of the own body and attitudes about it reported that a user's individual body characteristics, either on its own or in combination with application-related factors, can significantly affect the perception of virtual humans. In consequence, different implications can be derived. The influence of potential self-identification-based double standards should be considered when designing XR applications involving personalized or embodied virtual humans. In conjunction with the work of Thaler et al. (2018a) and Wolf et al. (2020), results showed that embodiment and personalization can significantly influence users' body weight perception depending on their own body weight, leading to unintended consequences that need to be considered when designing for a particular use case. For example, when using XR technologies to asses body weight perception neutrally following the principle of figure rating scales (Mölbert et al., 2017a), the use of personalization and embodiment should be avoided to prevent uncontrolled influences and to increase comparability to analog methods. On the other hand, employing personalization and embodiment can be considered when investigating self-perception. Furthermore, when employing virtual human embodiment to cause perceptual changes through a potential "perceptual" Proteus effect, application designers need to consider that the embodied virtual human, in its function as a stimulus, might be perceived differently depending on the user's own body and the attitudes about it. Another important implication is that attitudes regarding the own body can influence the perception of virtual humans, particularly when personalization is involved. As mentioned in the section above, offering customization options regarding stylism and personalization might address this issue. Overall, the perception of virtual humans is highly dependent on their users, suggesting that adaptation possibilities for individual needs and preferences should always be considered in the application design, particularly when employing virtual humans in serious applications.

The section about discovering system-induced biases pointed out that a display bias can lead to severe differences in the perception of a virtual human's body weight. Therefore, application designers need to carefully consider the choice of display technology and its inherent biases when developing applications involving body weight perception. For example, to ensure reliable and accurate body weight estimations, it appears crucial to validate the accuracy of the used XR display as quality criteria based on large sample sizes. By determining system-specific deviation parameters, interindividual misestimations might be better interpretable. This validation process becomes particularly important when testing user groups with potential or confirmed disturbed body perception. Additionally, providing context and transparency about possible biases seems crucial. In this regard, the reader is referred to the work of Tseng et al. (2022), who summarized the negative aspects of perceptional manipulations in VR. Although the authors mainly focused on physical consequences, they highlighted the users' consent and awareness of performed manipulation as crucial. This disclosure was also relevant in the context of this dissertation, as exposing participants intentionally or unintentionally to an embodied virtual human with modified body weight without making them aware of this manipulation can lead to unpredictable effects on their body perception through a potential "perceptual" Proteus effect. By understanding display-related biases, application designers can strategically leverage the Proteus effect to facilitate perceptual changes, assuming the bias is acknowledged and appropriately addressed either in the application design or in the system composition.

The Role of the Virtual Mirror

As introduced in the section on application-related factors that can influence the perception of virtual humans in VEs, recent analyses on the usefulness of virtual mirrors in virtual human embodiment yielded mixed results regarding its reinforcement effect for the SoE (Bartl et al., 2022; Döllinger et al., 2023b; Mottelson et al., 2023) and questioned its necessity for several use cases. However, other works have shown that the virtual mirror is indispensable for reflecting the allocentric perspective in scenarios where the focus lies on the external appearance of the virtual body (Neyret et al., 2020a; Thaler et al., 2019). Due to these works, it has been decided to incorporate a mirror in all of the dissertation's chapters that employed virtual human embodiment. The observations made by the experimenter and the qualitative feedback provided by the participants during the studies confirmed the mirror's importance in the works presented here. However, in Chapter 4, concerns arose about whether observed differences in body weight perception between two devices could also be attributed to an uncontrolled allocentric SOD. A literature screening revealed that there was neither previous work on the influence of the SOD on body perception nor SoE and affective appraisal. Hence, this topic got addressed in Chapter 3. The results revealed that the SOD did not significantly affect SoE, body weight perception, or affective appraisal of the avatar within a range of one to four meters. This finding is valuable for practical application, as it suggests that uncontrolled distances within the tested range are unlikely to confound studies that do not consider SOD as a factor.

The Potential of Virtual Human Embodiment in AR

The findings presented in Chapter 4 regarding virtual human embodiment in AR yielded unexpected results leading to valuable implications for the area of body perception and beyond. The hypothesis expected that virtual human embodiment in AR, facilitated by the Microsoft HoloLens 2 (Microsoft, 2019a), would lead to a significantly lower SoE compared to VR. However, results showed that the continuous possibility of comparing the real body to the virtual body, presented in the holographic AR mirror, and the limited field of view did not significantly impact VBO. Furthermore, they revealed that the feeling of agency over the virtual body in AR might be more resilient than anticipated. The perceptible latency of the virtual human's movements in the mirror in direct comparison to the latency-free unmediated first-person perspective on the real body did not lead to a reduced feeling of agency over the virtual human compared to VR, where the first-person perspective on the virtual human also exhibits latency. Maintaining a connection to the real environment, directly comparing the virtual and real body, and interacting with non-immersed others while preserving the SoE

Figure S7: Exemplary illustration of an AR mirror showcasing the potential of virtual human embodiment in AR for supporting body perception.

towards the virtual body opens up enormous possibilities in various fields. Figure S7 shows an exemplary use case for supporting body perception. However, it is important to note that these implications are based on one investigation only and further research is needed to consolidate the findings. For example, in Chapter 4, the body movements have been captured markerless. If an equivalent system is not available, the question arises whether the visibility of the required trackers or tracking markers through AR influences the UX or SoE. Additionally, the observed low SoP and its impact on the efficacy of potential behavioral, attitudinal, or perceptual changes require more investigation, as the existing literature in this area is sparse (Genay et al., 2021).

Observed Influences on the UX of XR Applications

Although this dissertation primarily focused on investigating the perception of virtual humans in VEs, it also captured the impact of the performed experimental manipulations on the general XR experience, mainly on SoP. The following section provides a brief overview of the results while directing readers to the corresponding chapters for more detailed information. From the results of Chapter 1, it could be concluded that performing rapid and potentially implausible body weight modifications on virtual humans might decrease an XR experience's overall plausibility (Latoschik & Wienrich, 2022), as SoP scores were relatively low compared to related work (Buttussi & Chittaro, 2018; Wolf et al., 2020). Chapter 2 showed that employing virtual human embodiment affects SoP positively. This finding confirms the results of prior empirical work (S. Jung & Hughes, 2016) and is in line with assumptions of the CaP model (Latoschik & Wienrich, 2022), suggesting that having a humanoid virtual body moving in synchrony with our real body matches our real-world expectations, leading to a plausible XR experience that increases SoP. Chapter 4 and Chapter 5 captured the influence of different immersive XR experiences on SoP, confirming the widely accepted relationship that a higher immersion usually leads to a higher SoP (Cummings & Bailenson, 2016). The CaP model further posits that the coherence and plausibility of an XR experience also influence its SoP. In this regard, the interviews performed in Chapter 4 highlighted a discrepancy between the appearance of the virtual humans in the virtual mirror and the real environment, possibly affecting the experience's plausibility. In detail, participants found the virtual mirror highly salient due to its transparency, image quality, and computer-animated reflection, but also perceived incongruency when seeing their real body in comparison to the virtual body. These qualitative reports have also been reflected in the igroup presence questionnaire (IPQ) realism score, showing the lowest scores for the most incongruent condition (OST AR). Chapter 5 further elaborated on this finding, including the virtual human plausibility questionnaire (VHPQ) of Mal et al. (2022) as a direct subjective measure of the virtual human's impact on the experience's plausibility. In VR, the concurrency between the rendered virtual human and the rendered VE resulted in higher plausibility, while in AR, the incongruency between the rendered virtual human and the real environment resulted in a significantly lower plausibility. Overall, Chapter 4 and Chapter 5 confirmed the theoretical assumptions of the CaP model (Latoschik & Wienrich, 2022) and are consistent with the recently introduced taxonomy for describing XR experiences by Skarbez et al. (2021b).

Technical Contributions

Besides the numerous valuable insights into the different factors influencing the perception of virtual humans in VEs and their implications on the application design space, this dissertation also provides a significant technical contribution that will be summarized and discussed in the following. Chapter 1 introduced a high-fidelity prototype of an advanced VR system that enables users to embody a rapidly generated photorealistically personalized virtual human and to adjust its body weight realistically and interactively in real-time. The system is further capable of importing newly generated virtual humans at runtime for immediate use, seamlessly substituting the user's current virtual body representation. This approach also allows a potentially encrypted distribution of the virtual humans through a network connection when targeting multi-user experiences. The SteamVR-based support for VR HMDs (Valve, 2021) originally implemented in Chapter 1 was successively extended in different chapters to operate various AR HMDs based on other XR frameworks. To this end, the work presented in Chapter 4 integrated Microsoft's Mixed Reality Toolkit 2 (Microsoft, 2019b) to support the Microsoft HoloLens 2 and the work presented in Chapter 2 the Varjo Base 3 interface (Varjo, 2021a) to support the Varjo XR-3. By extending the system to support AR, seamless switching between VR and AR for devices supporting both experiences has been incorporated. Additionally, an environment calibration feature based on the Kabsch algorithm (Müller et al., 2016), which automatically aligns virtual environments with the real-world environment, facilitating accurate blending of virtual and real elements by precisely matching their positions, has been added in Chapter 3.

For the animation of virtual humans, the system presented in Chapter 1 relies on an IK-supported generation of body poses (Aristidou et al., 2018) based on a minimum set of tracking points (i.e., head, spine, hands, feet) that was initially implemented for the studies conducted in Wolf et al. (2020) and Chapter 2. In Chapter 4 and Chapter 5, the system was further extended to support the markerless motion tracking system from Captury (Captury, 2021; Stoll et al., 2011) and the recording and playback of animation sequences, respectively. Overall, the developed virtual human animation system allows merging the captured information from different animation sources for each body part, creating a master "virtual human pose" object that can be retargeted and adapted to a theoretically infinite number of virtual humans only limited by the performance of the computing workstation. The virtual human animation system further supports network distribution of the animations following the principles of the work of Latoschik et al. (2019), thereby enabling the implementation of multi-user experiences. A first work employing the system for multi-user experiences realizing a scenario for swapping the body representation with another user is currently in preparation for publication (Döllinger et al., 2024a). Figure S8 sketches the abstracted architecture of the virtual human animation system developed throughout the different chapters.

In addition to the chapters of this dissertation, the developed system has been successfully used to conduct experiments in numerous other scientific works listed below. Due to its flexible and largely modular design, the system has been easily adapted and extended to the requirements of these works. With regard to the implementation of the changes, the author of this dissertation was actively involved in both advisory and executive roles. In the work of Döllinger et al. (2022b), the capabilities of the Vive Pro Eye HMD (HTC, 2018b) have been integrated into the system. By leveraging the provided eye-tracking data, embodied virtual humans' eye and eyelid movements could be animated in real-time. The mouth area has also been vivified using lip synchronization based on the recorded voice. In the works of Döllinger et al. (2022b, 2023b), Mal et al. (2023), and Fiedler et al. (2023a), which explored different aspects of virtual human embodiment, the embodied virtual human's fin-

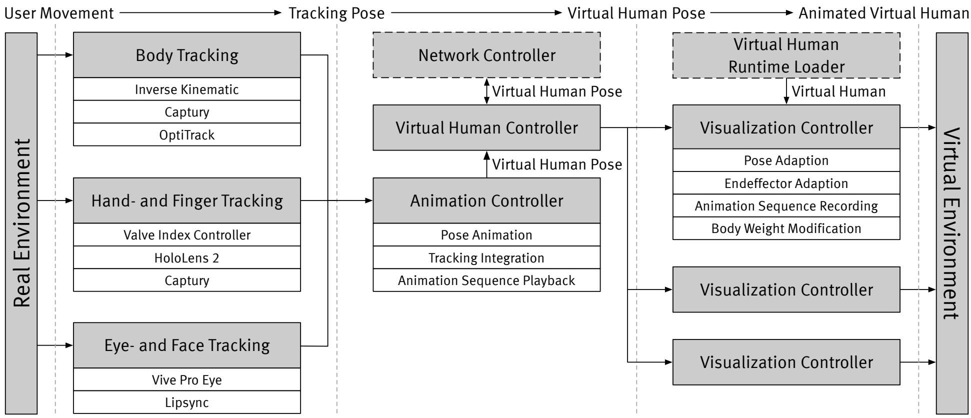

Figure S8: Abstracted architecture of the virtual human animation system depicting the process from capturing a user's movements in the real environment (left) to rendering its animated virtual human to the VE (right). The solid blocks show components implemented mainly by the dissertation's author and dashed blocks components implemented mainly by others. User movements are captured by different tracking solutions each passing a tracking pose to the animation controller. There, the poses get integrated into a complete virtual human pose that is passed to the user controller, where it replicates to n local visualization controllers. Additionally, it can also be sent to and received from the network controller. The visualization controller retargets the pose to a runtime-loaded virtual human, applies different optimizations, and shows it in the VE.

gers have been animated by taking the tracking data from the capacitive proximity sensors of the Valve Index controllers (Valve, 2020c). In the work of Mal et al. (2022) on virtual human plausibility, the system was used to record videos of different types of virtual humans always performing the same prerecorded animations integrated from a professional OptiTrack Flex 3 motion tracking system. A follow-up study utilizing the developed system to extend the results to real-time rendered VR experiences is currently under review (Mal et al., 2024b). By taking advantage of the easy and flexible retargeting of real-time virtual human animations, the concurrent embodiment of multiple virtual humans has been realized in the work of Bartl et al. (2021b). This study compared the perception of two differently reconstructed virtual humans by simultaneously embodying participants in both virtual humans and providing an allocentric perspective for each virtual human through separate virtual mirrors, facilitating a direct comparison of their appearances. The developed system has further been used in the work of Bartl et al. (2021a) and numerous other studies, some of which are currently under review (Döllinger et al., 2023a) or in preparation for publication (Döllinger et al., 2024b, 2024a; Fiedler et al., 2024; Mal et al., 2024a).

Future Directions

In addition to the numerous findings and implications presented in this dissertation, there are also certain limitations that motivate future work. In the following, we highlight four main directions that can serve as entry points for further research and development.

Improving Measurement Tools

Most of the tools used for capturing the perception of XR experiences and virtual humans in our and analyzed related work rely on subjective self-assessments using Likert scale-based items (Likert, 1932). While these items allow for simple, standardized, and flexible elicitation of user perception, they also possess several drawbacks. Likert items often lack the required granularity (Pearse, 2011), can be subject to social desirability bias (Krumpal, 2013), and are often hard to interpret through their standardized formulation not fitting to or being influenced by a particular context (Tourangeau & Rasinski, 1988). Furthermore, the intervals between choices on Likert scales should usually not be quantified metrically, although this is common practice (Jamieson, 2004). Assessing the perception of virtual humans through metric-scaled performance measures within experimental tasks, as we have established as a method in Chapter 5, could provide a practical and more objective alternative to using Likert scale items. Additionally, incorporating qualitative interview questions, as done in Chapter 1 and Chapter 4, and analyzing them with methods such as thematic analysis (Braun & Clarke, 2006) can yield additional valuable and unexpected feedback that might remain hidden when using purely quantitative questionnaire items. Hence, future work should capture and consider more behavioral, observational, or physiological data. Nevertheless, it can be expected that Likert item-based scales will continue to be necessary practice. Therefore, standardized and validated tools should always be preferred to improve their use. In this regard, recently established questionnaires, such as the virtual embodiment questionnaire (VEQ) introduced by D. Roth and Latoschik (2020) or the VHPQ (Mal et al., 2022), should be considered for revalidation based on a larger amount of data. In addition, the extensions of the VEQ by the dimensions of self-location, self-attribution, and self-similarity proposed in Chapter 3 still require careful psychometric validation for further use. In terms of capturing the overall quality of an XR experience, we found that most instruments for capturing presence and related concepts, such as the well-established IPQ (Schubert et al., 2001), emerged in the early 2000s. Although the latest concepts for the classification of XR experiences by Skarbez et al. (2021b) and Latoschik and Wienrich (2022) can still be partially reconciled with these instruments, it seems obvious that a revision of the measurement methods is timely in order to consider all aspects of the new concepts and to avoid interpretation ambiguities.

Investigating Reasons for System-Related Biases

Chapter 4 and Chapter 5 reported significant disparities in the perception of virtual humans across different XR systems. While recognizing such perceptual distortions already allow their adjustment in the application design space, future XR systems should aim to convey the content of VEs with little to no distortion. Since results suggest that the properties that also affect the system's degree of immersion cause such distortions, a careful investigation through manipulation of specific system properties seems inevitable to uncover their concrete source and improve the fidelity of future XR systems. In this regard, utilizing body weight estimations based on modified virtual humans, as proposed in Chapter 5, offers a valid way to quantify the specific influences more precisely.

Incorporating Technical Advancements

Since starting the development of the technical system utilized in this dissertation, the technical enhancements in the field of XR and virtual humans have progressed steadily. By integrating recently published scientific advances and leveraging further improved hard- and software components, notable improvements in general usability, UX, and the perception of virtual humans can be expected. For example, the recent acceleration in the research and development of artificial intelligence has revealed several approaches for full-body pose estimation based on sparse tracking information (Du et al., 2023; Jiang et al., 2022; Oreshkin et al., 2022). By utilizing tracking data only from the head, spine, and hands, these approaches can approximate the entire body pose and thus implement virtual human embodiment without the need for a comprehensive body tracking system. Consequently, operating a high-quality embodiment system becomes more accessible, making home use a viable option. Furthermore, the recent generation of XR HMDs, such as the Meta Quest Pro (Meta, 2022), offers enhanced tracking capabilities in the head area. By utilizing the eye- and face-tracking data provided, personalized blend shapes (Menzel et al., 2022) can be controlled to tackle the discussed problem of emerging uncanniness through missing animation in the facial area. Regarding body perception, the realism of body weight modifications can be further improved. For example, advanced simulation models include the individual body composition of fat and muscle tissues (Kadleček et al., 2016; Maalin et al., 2020) or allow separate modification of specific body parts (Pujades et al., 2019). Technologies for haptic weight simulation on the user's body, such as the one proposed by Kalus et al. (2023), can enhance the holistic perception of these modifications.

Diversifying the User Population

The performed research highlighted the substantial influence of the user's body appearance and attitudes about it on the perception of virtual humans within XR experiences. Accordingly, the composition of the user group used for testing and evaluating systems plays a major role. The conducted empirical work mainly involved samples of averagely proportioned young students, only containing a few outliers. However, as reported, it is known that user groups that show pathological deviations from average weight often also suffer from a distorted body perception or that age can significantly impact self-assessment. While the uncovered effects are mainly related to the tested samples, it is reasonable to expect that they may be even more pronounced in pathological samples. Accordingly, diversifying the test population is inevitable to further investigate and improve the perception of virtual humans, especially in the context of body perception. In this regard, the system presented in Chapter 1 has already been tested in a feasibility study with an obese sample not undergoing treatment as part of the ViTraS project. However, the data had neither been comprehensively analyzed nor published at the time this dissertation was completed. Including pathological user groups also opens up opportunities for exploring further use cases, such as applications in clinical scenarios targeting body misperception.

Conclusion

The research presented in this dissertation provides valuable insights into the different factors influencing the perception of virtual humans in VEs. Through an extensive literature analysis and the conducted user studies, it sheds light on individual-, system-, and application-related aspects as well as their interplay. One of the major findings is that the appearance of the user's own body and the attitude about it significantly influence the visual perception of virtual humans, especially when they are personalized or embodied. Moreover, the discovered display bias emphasizes the substantial impact the employed XR system can elicit on the perception of virtual humans. Based on the main findings and the further presented results, we have derived several implications that can guide future development and evaluation processes of XR systems that employ virtual humans in the domain of body perception and beyond. In this context, the potential of AR has been highlighted in particular. The presented findings can further help better understand how virtual humans need to be utilized to improve the overall UX of XR applications. Lastly, the presented technical contributions paved the way for developing sophisticated XR applications involving virtual humans, particularly in the context of body perception.

Chapter 1

Exploring the User Experience of Embodied Realistic Modulatable Avatars for Body Image Intervention in Virtual Reality

This chapter has been published as follows:[1]

Döllinger, N., Wolf, E., Mal, D., Wenninger, S., Botsch, M., Latoschik, M. E., & Wienrich, C. (2022c). Resize me! Exploring the user experience of embodied realistic modulatable avatars for body image intervention in virtual reality. *Frontiers in Virtual Reality*, *3*. https://doi.org/10.3389/frvir.2022.935449x

Figure C1.1: The images show a participant's personalized avatar standing in front of a mirror within the virtual exposition environment of our concept prototype with a reduced (left), normal (center), or increased (right) body weight.

[1] As part of the dissertation, the published text was editorially revised, with only slight orthographic, stylistic, and formal adjustments, while completely retaining the original semantics.

Abstract

Obesity is a serious disease that can affect both physical and psychological well-being. Due to weight stigmatization, many affected individuals suffer from body image disturbances whereby they perceive their body in a distorted way, evaluate it negatively, or neglect it. Beyond established interventions such as mirror exposure, recent advancements aim to complement body image treatments by the embodiment of visually altered virtual bodies in virtual reality (VR). We present a high-fidelity prototype of an advanced VR system that allows users to embody a rapidly generated personalized, photorealistic avatar and to realistically modulate its body weight in real-time within a carefully designed virtual environment. In a formative multi-method approach, a total of 12 participants rated the general user experience (UX) of our system during body scan and VR experience using semi-structured qualitative interviews and multiple quantitative UX measures. Using body weight modification tasks, we further compared three different interaction methods for real-time body weight modification and measured our system's impact on the body image relevant measures body awareness and body weight perception. From the feedback received, demonstrating an already solid UX of our overall system and providing constructive input for further improvement, we derived a set of design guidelines to guide future development and evaluation processes of systems supporting body image interventions.

Keywords

Virtual reality, avatar embodiment, user experience, body awareness, body weight perception, body weight modification, body image disturbance, eating and body weight disorders

1.1 Introduction

Obesity is a complex chronic disease characterized by severe overweight and an above-average percentage of body fat (World Health Organization, 2019). Its prevalence has more than doubled within recent decades and is expected to rise (Venegas & Mehrzad, 2020; World Health Organization, 2016). Besides the physical burdens (e.g., an increased risk of several secondary diseases, Stefan et al., 2021), affected individuals deal with an external or internalized stigmatization that can lead to body image disturbances (Meadows & Calogero, 2018; Rosen, 2001; J. K. Thompson & Tantleff-Dunn, 1998). Body image disturbances are composed of a misperception of body dimensions (body image distortion) and the inability to like, accept, or value one's own body (body image dissatisfaction) and are also associated with a reduced body awareness (Todd et al., 2019b; Turbyne et al., 2021). Various interventions (e.g., cognitive-behavioral therapy supported by mirror exposition or fitness training) have been designed to target persisting disturbances but often only achieve small improvements in the body image (Alleva et al., 2015). In recent years, novel VR-based methods complementing the therapy of body image disturbances have successfully been explored in research with promising results (Ferrer-Garcia et al., 2013; Riva et al., 2019; Wiederhold et al., 2016). The further improvement of these approaches in the context of obesity forms the current work's frame.

VR-based approaches for supporting body image interventions often use 3D models of human beings (Horne et al., 2020; Turbyne et al., 2021), so-called avatars (Bailenson & Blascovich, 2004). VR in general, and the confrontation with embodied avatars in particular, have great potential to influence human perception and behavior (Ratan et al., 2020; Wienrich et al., 2021a; Yee & Bailenson, 2007). In the context of body image, avatars have been utilized to expose users of a VR system to generic virtual bodies or body parts varying in size or shape to investigate the principles of body weight perception (Thaler, 2019; Wolf et al., 2020, 2021, 2022b) or to influence the perception or attitude towards the user's own body (Turbyne et al., 2021). Recent developments in computer graphics allow for the generation of photorealistic avatars that match a person's real-life appearance within a short duration at a low-cost (Achenbach et al., 2017; Bartl et al., 2021b; Wenninger et al., 2020) and for a realistic modulation of body dimensions in pictures and videos (Tang et al., 2021; Xiao et al., 2020; Zhao et al., 2018; Zhou et al., 2010) or in VR (Hudson et al., 2020; Maalin et al., 2020; Piryankova et al., 2014a). However, no work has yet been presented where users embody their photorealistically personalized avatar in VR while also having the ability to manipulate that avatar's body shape in real-time actively, nor has the impact of such a system on the users and their experiences been evaluated.

To address this gap, we present the development of a VR system allowing users to embody a photorealistic, personalized avatar within a virtual environment and to actively modify its body weight in real-time using different interaction methods. In a further step, we evaluated the system with regard to a later usage in clinically relevant settings within our research project Virtual Reality Therapy by Stimulation of Modulated Body Perception (ViTraS, Döllinger et al., 2019). In particular, we performed a formative user evaluation of the avatar generation process and interactive VR exposure with a small sample of healthy participants. Following Wienrich and Gramlich (2020) and considering the future potential user group, we assessed relevant factors such as security, physical comfort, accessibility, usability, and user experience, which we also already considered during the development process. Based on our evaluation's results, we derive a set of design guidelines for the future design and development of similar avatar-based body image therapy support tools.

1.2 Related Work

Body image disturbance is characterized by an "excessively negative, distorted, or inaccurate perception of one's own body or parts of it" (World Health Organization, 2019). It may manifest in body image distortion, the misperception of one's body weight and dimensions that have repeatedly been reported based on underestimations (Maximova et al., 2008; Valtolina, 1998) or overestimations (Docteur et al., 2010; Thaler et al., 2018a), or body image dissatisfaction, a negative attitude towards the body that is associated with body image avoidance (Walker et al., 2018) and reduced body awareness (awareness for bodily signals, Peat & Muehlenkamp, 2011; Todd et al., 2019a, 2019b; Zanetti et al., 2013). While often caused by internalized weight stigma and a fear of being stigmatized by others (Meadows & Calogero, 2018), body image disturbance interferes with efforts to stabilize body weight in the long term (Rosen, 2001). Treatments for body image disturbance mainly rely on cognitive-behavioral therapy, typically combining psychoeducation and self-monitoring tasks, mirror exposure, or video feedback (Farrell et al., 2006; Griffen et al., 2018; Ziser et al., 2018). Based on the fundamentals of these established methods, an increasing number of researchers have started to explore VR applications as additional support for attitude and behavior change in general (Wienrich et al., 2021a) and therapy of body image disturbance (Ferrer-Garcia et al., 2009, 2013; Riva, 1997; Riva et al., 2019; Turbyne et al., 2021) and obesity in particular (Döllinger et al., 2019; Horne et al., 2020).

1.2.1 The Unique Potential of Modulatable Avatars in VR

VR offers the opportunity to immerse oneself in an alternative reality and experience scenarios that are otherwise only achievable via imagination. Endowed with this unique power, mainly the use of avatars has attracted attention in treating body image disturbance (Horne et al., 2020; Turbyne et al., 2021). Image processing methods for simulating body changes are well established. Using parametric models, it is possible to retouch images to simulate different face or body shapes (Zhao et al., 2018; Zhou et al., 2010) and even manipulate them in real-time during video playback (Tang et al., 2021; Xiao et al., 2020). Avatars in VR allow simulating rapid changes in body shape or weight in an immersive environment using life-sized avatars going beyond the presentation of pictures and videos. They enable further general investigation of body weight perception (Thaler, 2019; Wolf et al., 2020, 2021). While some researchers are using multiple generic avatars differing in body weight (Ferrer-Garcia et al., 2018; Keizer et al., 2016; Normand et al., 2011; Piryankova et al., 2014b; Preston & Ehrsson, 2018), others have developed methods for dynamic body weight modification in VR (Alcañiz et al., 2000; Hudson et al., 2020; Johnstone et al., 2008; Maalin et al., 2020; Neyret et al., 2020a; Nimcharoen et al., 2018; Piryankova et al., 2014a). A huge advantage when using advanced body weight modification methods is that the avatar's body weight can be realistically changed to a desired numeric reference value. For this purpose, mainly the body mass index calculated as BMI $=$ Body Weight in kg / (Body Height in m)^2 (World Health Organization, 2000) is used. One example is the work of Thaler et al. (2018a), who trained a statistical model to apply realistic BMI-based body weight modification to their generated personalized, photorealistic avatars. But also other factors like muscle mass could be included in such models (Maalin et al., 2020). However, while picture and video-retouching methods tend to focus on facial features, the statistical models of weight gain/loss of avatars in VR are usually trained on the whole body (Piryankova et al., 2014a) or neglect the head region completely (Maalin et al., 2020). For our system, we also learned a statistical model of weight gain/loss for the head region but kept small parts of the face region fixed to preserve the identity of the users when applying the body weight modification.

Besides the shape of the used avatar, application or system-related properties also might alter how we perceive the avatar, and particularly its body weight, in VR. Wolf et al. (2020) presented an overview of potentially influencing factors, noting that while the used display or the observation perspective might unintentionally alter body weight perception (Wolf et al., 2022b, 2022c), especially the personalization and embodiment of avatars hold potential for application in body image interventions. For example, Thaler et al. (2018a) found that the estimator's BMI influences body weight estimations of a realistic and modulatable avatar, but only when the avatar's shape and texture matched the estimator's appearance. This comes along with a recent review by Horne et al. (2020), who identified the personalization of avatars as an important factor when using avatars. For embodiment, Wolf et al. (2021) recently found, for example, that females' own BMI influences body weight estimations of a generic avatar only when embodying it.

1.2.2 User Experience of a VR-based Body Image Intervention

In the design process of a VR application, it is of utter importance to test the system's user experience (UX). UX refers to the sum of all perceptions and reactions of a user to the interaction with an interface before, during, and after its use (International Organization for Standardization, 2019). It combines a variety of hedonic qualities, such as the joy of the user during an experience, and pragmatic qualities, such as the efficiency of interactions. Concerning the UX evaluation of VR systems, it is suggested to include the assessment of further VR-specific variables (Tcha-Tokey et al., 2016; Wienrich & Gramlich, 2020), namely simulation sickness (Kennedy et al., 1993), the feeling of presence (Slater, 2009), and the feeling of embodiment (Kilteni et al., 2012). Concerning avatar-based body image interventions, particularly the user's feeling of embodiment towards their avatar is of interest (Turbyne et al., 2021). It can be evoked by visuomotor congruence, for example, when the user sees the avatar moving like their real body (Slater et al., 2009, 2010b) and is divided into the feeling of being inside (self-location), of owning (virtual body ownership), and of controlling (agency) an avatar (Kilteni et al., 2012).

In addition to a system's classical UX evaluation, it is important to embed the development into an iterative design process. This typically involves understanding and establishing the context of use, defining the requirements for use, developing prototypes, and an iterative evaluation. Wienrich and Gramlich (2020) recently presented the *appRaiseVR* framework for UX evaluation in VR, which adapts the general process of UX design to the context of VR. In their VR-adapted design cycle, they include four steps: (1) defining the setting of the experience, including the details of the system, the planned usage context, and the target user group; (2) defining the level of evaluation, including either an evaluation of the system itself, the task, the narrative, the effect on the user, or the relation between different users; (3) rating the plausibility of the experience, namely its realism, its virtual and physical components; and (4) selecting the time of measure, whether evaluating the expectancy towards a system, the immediate reaction within the experience a post-experience evaluation or follow-up assessments.

Considering this framework, our research evaluates a highly immersive VR system, including a realistic environment and photorealistic, modulatable avatars (1, 3). The design aims at a realistic, clinical setting with a target group dealing with obesity and a disturbed body image (1). Based on our target group, our evaluation focuses on security, physical comfort, and accessibility of our system, next to VR-specific UX and usability of different interaction tasks and the plausibility of avatar modifications (2), which we test during and after the experience (4).

In the context of our application, we further define the effects on body weight perception and physical body awareness during the use as essential parts of the users' experience. For example, Riva et al. (2019) stated that embodiment could potentially help update the misperception of body dimensions by experiencing the ownership over a differently shaped or sized avatar. This goes along with a recent review by Turbyne et al. (2021), summarizing that participants' body image conformed to a modified virtual body size when participants felt embodied in it. VR further interferes with the user's physical body awareness. Filippetti and Tsakiris (2017) showed an increase in body awareness when embodying an avatar for individuals with initially low body awareness. Döllinger et al. (2022b) revealed that especially the feeling of body ownership towards a personalized avatar is positively related to body awareness. However, there is no research on body awareness in a VR-based body image treatment task.

1.2.3 User Interaction for Body Weight Modification

Most VR applications for body image interventions aim for enhanced mirror confrontation. They surpass real mirror confrontation by modifying the mirror image or the shown avatars into different body shapes. In our system, we want to go one step further and allow users to adjust the shape of their avatar interactively. Our idea is to give users the opportunity to actively engage in analyzing their body image and develop a novel feeling for their own body. Object manipulation in VR has been widely researched and can serve as a reference in the development of body weight modification interaction methods. For example, LaViola et al. (2017) presented a set of design guidelines for different types of object manipulation, including object scaling by virtual buttons or other control elements, the inclusion of physical interfaces as provided on most VR controllers, or the design of gesture-based object manipulation. Furthermore, Williams et al. (2020) and H. Wu et al. (2019) investigated the preference of users towards different gestures in object manipulation, and both proposed using two-handed gestures (e.g., moving the hands apart or bringing them together) for size modification of large objects.

1.2.4 Summary and Outline

VR in general, and the embodiment of modulatable avatars in specific, hold great potential to innovate interventions for body image disturbances. The introduced research shows that there exist promising developments toward avatar-based interventions for body image disturbances. However, no work to date undertakes a comprehensive VR-specific UX investigation of such an intervention system.

Our current work within the interdisciplinary research project ViTraS (Döllinger et al., 2019) addresses this research gap and aims toward a novel approach for supporting body image therapy. We present a high-fidelity prototype of a body image therapy support system that allows users to embody their rapidly generated personalized, photorealistic avatar within a carefully designed virtual environment. Our system allows users to dynamically alter their body weight while being embodied in VR using three different interaction methods (joystick, gestures, and virtual objects). We focus on a user experience evaluation with normal-weight participants performed within our first design cycle. In a comprehensive mixed-methods evaluation, we assessed (1) the body scan experience during the avatar generation process, (2) the general, VR-specific UX of the exposure and different modification methods, and (3) their impact on body image-related UX, including body awareness and body weight perception. To sum up our results, we derive a set of guidelines for the design and implementation of future VR systems supporting body image interventions.

1.3 System Description

The technical implementation of our system is realized using the game engine *Unity* version 2019.4.15f1 LTS (Unity Technologies, 2019). As VR HMD, we use a *Valve Index* (Valve, 2020c), providing the user a resolution of 1440×1600 px per eye with a total field of view of $120°$ running at a refresh rate of 90 Hz. For motion tracking, we use the two handheld Valve Index controllers, one *HTC Vive Tracker 3.0* positioned on a belt at the lower spine, and one tracker on each foot fixed by a velcro strap. The tracking area was set up using four *SteamVR Base Stations 2.0*. All VR hardware is integrated using *SteamVR* in version 1.16.10 (Valve, 2021) and its corresponding Unity plugin in version 2.7.3 [2]. In our evaluation, the system was driven by a high-end PC composed of an *Intel Core i7-9700K*, an *Nvidia RTX2080 Super*, and *32 GB RAM* running *Windows 10*. To ensure that users always received a fluent VR experience and to preclude a possible cause of simulator sickness, we measured the motion-to-photon latency of our system by frame-counting (He et al., 2000; Stauffert et al., 2021). For this purpose, the video output was split into two signals using an *Aten VanCryst VS192* display port splitter. One signal still led to the HMD, the other to an *ASUS ROG SWIFT PG43UQ* low-latency gaming monitor. A high-speed camera of an *iPhone 8* recorded the user's motions and the corresponding reactions on the monitor screen at 240 fps. The motion-to-photon latency for the HMD matched the refresh rate of the used Valve Index closely, as it averaged 14.4 ms ($SD = 2.8$ ms). The motion-to-photon latency for the body movements was considered low enough to provide a high feeling of agency towards the avatar (Waltemate et al., 2016), as it averaged 40.9 ms ($SD = 5.4$ ms).

1.3.1 Virtual Environments

We realized two virtual environments. The first environment replicates the real environment, in which the user was located physically during our evaluation, and which is automatically calibrated accurately to overlay the physical environment spatially (see Figure C1.2). Here, all preparatory steps required for exposure are performed and tested (e.g., ground calibration, vision test, equipment adjustments, embodiment calibration). For spatial calibration, we use

[2] https://assetstore.unity.com/packages/tools/integration/steamvr-plugin-32647

Figure C1.2: The figure depicts a comparison between the real environment where the experiment took place (left) and the replicated virtual environment used for preparation (right). Both environments contain a user, respectively the avatar, performing the embodiment calibration.

a customized implementation of the Kabsch algorithm [3] (Müller et al., 2016), based on the positions of the SteamVR base stations in real and virtual environments. Additionally, the virtual ground height is calibrated by briefly placing the controller onto the physical ground.

The second environment is originally based on an asset taken from the Unity Asset Store [4] that was modified to match our requirements. This exposition environment is inspired by a typical office of a psychotherapist with a desk and chairs and an exposure area in which the mirror exposure takes place (see Figure C1.1). The exposure area includes a virtual mirror allowing for an allocentric observation of the embodied avatar. We aimed for a realistic and coherent virtual environment to enhance the overall plausibility of the exposure (Latoschik & Wienrich, 2022; Slater, 2009).

1.3.2 Generation and Animation of Personalized Avatars

In our system, the user embodies a personalized avatar from an egocentric perspective while the avatar is animated according to the user's body movements in real-time. The following sections describe the generation of the avatars as well as the animation system.

[3] https://github.com/zalo/MathUtilities#kabsch
[4] https://assetstore.unity.com/packages/3d/props/interior/manager-office-interior-107709

Generation Process

The generation of the avatars closely follows the method of Achenbach et al. (2017). First, the subject is scanned with a custom-made photogrammetry rig consisting of 94 DSLR cameras, where four studio lights equipped with diffuser balls ensure uniform illumination (Bartl et al., 2021b). Instead of employing a separate face scanner like Achenbach et al. (2017) did, ten of the 94 DSLR cameras are zoomed in on the subject's face to capture more detail in this region. The images taken by the cameras are then automatically processed with the commercial photogrammetry software Agisoft Metashape (Agisoft, 2021), resulting in a dense point cloud of the subject. We manually select 23 landmarks on the point cloud in order to guide the subsequent template fitting process. The counterparts of these landmarks are pre-selected on the template model, which comes from the Autodesk Character Generator (Autodesk, 2014) and consists of $N \approx 21k$ vertices, an animation skeleton with skinning weights, facial blendshapes, as well as auxiliary meshes for eyes and teeth. Achenbach et al. (2017) enhance the template with a statistical model of human shape variation. This statistical, animatable human template model is then fitted to the point cloud by optimizing for alignment, pose, and shape by employing non-rigid ICP (Bouaziz et al., 2014). This optimization of the model parameters defines the initial registration of the template, which is then further refined by allowing fine-scale deformation of the vertices to match the scanner data more closely. For more details, we refer to Achenbach et al. (2017).

Animation Process

For avatar animation, the participants' movements are continuously captured using the SteamVR motion tracking devices. The tracking solution provides for our work a sufficiently solid and rapid infrared-based tracking solution for the crucial body parts required for animation without aligning different tracking spaces (Niehorster et al., 2017). To calibrate the tracking devices to the user's associated body parts and capture the user's body height, arm length, and current limb orientations, we use a custom-written calibration script that requires the user to stand in T-pose for a short moment (see Figure C1.2). The calibrated tracking targets of the head, left hand, right hand, pelvis, left foot, and right foot were then used to drive an Inverse Kinematics (IK, Aristidou et al., 2018) approach realized by the Unity plugin FinalIK version 2.0 [5]. FinalIK's integrated VRIK solver continuously calculates the user's body pose according to the provided tracking targets. The tracking pose is automatically adjusted to the determined body height and arm length in order to match the user's body. In the next step, the tracking pose is continuously retargeted to the imported personalized avatar.

[5]https://assetstore.unity.com/packages/tools/animation/final-ik-14290

Potentially occurring inaccuracy in the alignment of the pose or the end-effectors can be compensated by a post-retargeting IK-supported pose optimization step. This leads to high positional conformity between the participant's body and the embodied avatar and avoids sliding feet due to the retargeting process.

1.3.3 Body Weight Modification of Avatars

Our system allows the user to modify their body weight during runtime dynamically. The statistical model of weight gain/loss and the implemented user interaction methods are described in the following.

Data-driven Body Weight Modification

To build a statistical model of body weight modification, we follow the approach of Piryankova et al. (2014a), who first create a statistical model of body shape using principal component analysis (PCA) and then estimate a linear function from anthropometric measurements to PCA coefficients. For computing the statistical model of human body shape, we use the template fitting process described above to fit our template model to the European subset of the CAESAR scan database (Robinette et al., 2002). It consists of $M = 1700$ 3D scans, each annotated with anthropometric measurements such as weight, height, arm span, inseam, waist width, etc. After bringing the scans into dense correspondence via template fitting, we are left with M pose-normalized meshes consisting of N vertices each. Our approach for data-driven weight gain/loss simulation differs from the method of Piryankova et al. (2014a) in the following ways: (1) Instead of encoding body shape as a 3×3 deformation matrix per mesh face (Anguelov et al., 2005), we encode body shape directly via vertex positions. (2) Modelling weight gain/loss as a change in parameters of a statistical parametric shape model (Piryankova et al., 2014a; Xiao et al., 2020) changes face identity during weight modification due to the fact that the learnt direction of change is not subject-specific. This leads to effects such as changing the shape of the eye socket, the pupillary distance or other unrealistic changes in face proportions. To mitigate these effects, we keep vertices in the face region fixed while deforming the rest of the mesh in order to preserve the identity of the participants.

To this end, we define a set $\mathcal{S}$ with cardinality V containing all vertices outside of the face region (see Figure C1.3) as well as a selector matrix $\mathbf{S} \in \mathbb{R}^{3V \times 3N}$ which extracts all coordinates belonging to vertices in $\mathcal{S}$. Let $\mathbf{x}_j = \left(\mathbf{p}_1^T, \ldots, \mathbf{p}_N^T\right)^T \in \mathbb{R}^{3N}$ be the vector containing the stacked vertex positions of the j^{th} training mesh and $\bar{\mathbf{x}} = \frac{1}{M} \sum_j \mathbf{x}_j \in \mathbb{R}^{3N}$ be the corresponding mean. Performing PCA on the data matrix $\mathbf{X} = \Big(\mathbf{S}\mathbf{x}_1 - \mathbf{S}\bar{\mathbf{x}}, \ldots, \mathbf{S}\mathbf{x}_M - \mathbf{S}\bar{\mathbf{x}}\Big) \in$

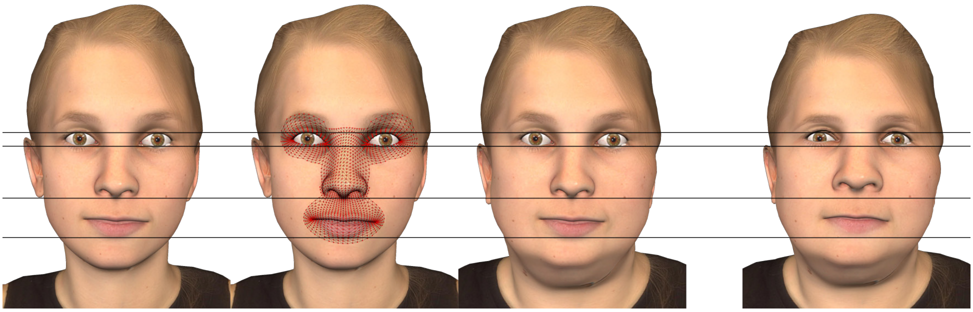

Figure C1.3: The figure illustrates our approach of facial weight gain simulation. When modifying the weight of an avatar (left), part of the face region (highlighted in red) is fixed (center left). The modified vertices are stitched to the face region in a seamless manner using differential coordinates (center right, Sorkine, 2005). Not keeping these vertices fixed would require recalculating the position of all auxiliary meshes such as eyes and teeth due to the undesired change in facial proportions for nose, mouth and eyes stemming from changing the parameters of the underlying face model (right). For the right image, eyes are copied from the unmodified avatar in order to better highlight the change in shape and position.

$\mathbb{R}^{3V \times M}$ and taking the first $k = 30$ components then yields the PCA matrix $\mathbf{P} \in \mathbb{R}^{3V \times k}$. Let $\mathbf{W} = \left(\mathbf{w}_1, \ldots, \mathbf{w}_M\right) \in \mathbb{R}^{k \times M}$ contain the PCA coefficients $\mathbf{w}_j$ of the M training meshes, computed by $\mathbf{w}_j = \mathbf{P}^T \left(\mathbf{S}\mathbf{x}_j - \mathbf{S}\bar{\mathbf{x}}\right)$. If we denote by $\mathbf{D} \in \mathbb{R}^{M \times 4}$ the matrix containing the anthropometric measurements weight, height, armspan and inseam of the j^{th} subject in its j^{th} row, we can then compute a linear mapping from anthropometric measurements $\mathbf{D}$ to PCA coefficients $\mathbf{W}$ by solving the linear system of equations $\left(\mathbf{D} \mid \mathbf{1}\right) \mathbf{C} = \mathbf{W}^T$ in a least-squares sense via normal equations.

New vertex positions for a subject with initial vertex positions $\mathbf{x}$ and a desired change in anthropometric measurements $\Delta\mathbf{d} \in \mathbb{R}^5$ can then be calculated via $\tilde{\mathbf{x}} = \mathbf{S}\mathbf{x} + \mathbf{P}\left(\mathbf{C}^T \Delta\mathbf{d}\right)$, i.e., by first projecting the desired change in measurements into PCA space via the learned linear function and then into vertex position space via the PCA matrix. However, this only updates vertices in $\mathcal{S}$. In order to seamlessly stitch the new vertex positions to the unmodified face region, we compute the Laplacian coordinates (discretized through cotangent weights and Voronoi areas, Botsch et al., 2010) of the resulting mesh and then use surface reconstruction from differential coordinates (Sorkine, 2005). For the vertices of the face region and its 1-ring neighborhood, the Laplacian is computed based on the unmodified vertex positions $\mathbf{x}$, while for the rest of the vertices, the Laplacian is computed based on the modified vertex positions $\tilde{\mathbf{x}}$. Since the position of vertices of the face region is known and should not change, we treat the position of these vertices as *hard* instead of *soft* constraints as discussed by Botsch and

Figure C1.4: The figure shows a generated female avatar (BMI $= 19.8$) with modified body weight corresponding to a BMI range of 16 to 32 in two-point increments.

Sorkine (2008). Setting $\Delta\mathbf{d} = \left(\Delta w, 0, 0, 0, 0\right)^T$ then allows modifying the user's weight while keeping the other anthropometric measurements fixed. Keeping the face region fixed (1) preserves the identity of the user for high values of Δw and (2) avoids having to recalculate the position of auxiliary meshes of the avatar such as eyes and teeth (see Figure C1.3). Results of the described body weight modification method are shown in Figure C1.4.

Interaction Methods

To allow users to modify the avatars' body weight as quickly, easily, and precisely as possible, we compare in our evaluation three implemented interaction methods regarding their usability. Since interaction methods for human body weight modification have not yet been explored, we considered the guidelines for object modification presented by LaViola et al. (2017). Figure C1.5 gives a short overview of the body weight modification methods. After a pilot test of body weight modifications with multiple generated virtual humans, we restricted the body weight modification for all interaction methods to a range of $\pm 35\,\%$ of the user's body weight to avoid unrealistic, possibly unsettling shape deformation. To avoid providing any hidden cues, we have extended the possible modification range compared to the used modification range of our passive estimation task. The constants given in the formulas for calculating the velocity of body weight change were determined empirically in a further pilot test.

Figure C1.5: The figure sketches the three body weight modification methods we used for our evaluation: Gestures (left), Joystick (center), and Objects (right).

Body Weight Modification via Controller Movement Gestures To modify the avatar's body weight via gestures (see Figure C1.5, left), users have to press the trigger button on each controller simultaneously. Moving the controllers away from each other then increases the body weight, while moving them towards each other decreases it. The faster the controllers are moved, the faster the body weight changes. When active, the body weight changes by the velocity v in kg/s, determined by the relative distance change between the controllers r in m/s, and calculated as $v = 3.5r^2 + 15r$.

Body Weight Modification via Joystick Movement To modify the avatar's body weight via joystick (see Figure C1.5, center), users have to tilt the joystick of either the left or the right controller. Selecting joystick for an initial modification leads to a deactivation of the other joystick for the remaining interaction. Tilting the joystick to the left decreases the body weight, tilting it to the right increases it. The stronger the joystick is tilted, the faster the body weight changes. When enabled, the body weight changes by the velocity v in kg/s, determined by the normalized tilt t of the joystick and calculated as $v = 10t^2 + 5$.

Body Weight Modification via Controller Movement Towards Objects To modify the avatar's body weight via objects (see Figure C1.5, right), users have to touch either a virtual "plus" or a virtual "minus" object within the virtual environment. As long as an object is touched, the body weight increases or decreases. The longer the object is touched, the faster the body weight changes. When active, the body weight modification velocity v in kg/s increases quadratically over a normalized contact duration d of 1.5 s in a normalized range r between 3 kg/s and 15 kg/s.

1.4 Evaluation

We tested our first system prototype in a structured UX evaluation based on multiple relevant qualitative questions and quantitative measures concerning the users' scan and VR exposure experience as well as their body image. The following sections contain a detailed explanation of the evaluation process.

1.4.1 Ethics

Since our technical system was developed with the aim of being tested on potential patients in a clinically relevant context as part of a later feasibility study, particular attention has already been paid to ethical aspects during the here reported development and evaluation of our system. As part of a conservative development and evaluation strategy, we decided to work with a relatively small sample of healthy participants in this initial formative evaluation. The system, as well as the evaluation, was designed in consultation with our clinical partners within the context of our interdisciplinary research project ViTraS (Döllinger et al., 2019). A detailed ethics proposal following the Declaration of Helsinki was submitted to the ethics committee of the Human-Computer-Media Institute of the University of Würzburg and found to be ethically unobjectionable. Free professional help services provided by the Anorexia Nervosa and Associated Disorders (ANAD) [6] organization were explicitly highlighted during the acquisition and evaluation process.

1.4.2 Participants

A total of 12 students (8 female, 4 male) of the University of Würzburg participated in our evaluation and received course credit in return. Before the evaluation, we defined four exclusion criteria queried by self-disclosure: Participants had to have (1) normal or corrected to normal vision and hearing, (2) at least ten years of experience with the German language, (3) not suffered from any kind of mental or psychosomatic disease, or from body weight disorders, and (4) no known sensitivity to simulator sickness. None of the participants matched any exclusion criteria. The participants were aged between 20 and 25 ($M = 22.0$, $SD = 1.48$), had a BMI between 17.85 and 32.85 ($M = 22.72$, $SD = 3.98$), and had mostly very little VR experience. Nine out of the twelve participants claimed to know their current body weight. The mean deviation of the indication of their body weight compared to that measured by the experimenter was 0.29 kg ($SD = 1.57$).

[6] https://www.anad.de/

1.4.3 Design

The evaluation of our system included qualitative and quantitative measures regarding (1) the body scan experience, (2) the UX of the VR exposure and the different modification methods used, and (3) their impact on the body image-related measures body awareness and body weight estimation. To compare our three modification methods (see Figure C1.5), participants performed for each modification method a set of active modification tasks (AMTs) in a counterbalanced order using a 3×1 within-subjects design. For comparing the novel AMT with the more traditional passive estimation task (PET), the participants performed a PET each before and after the AMTs (see Figure C1.6, right). All tasks and the timing of the measures will be further explained in Section 1.4.5.

1.4.4 Measures

Body Scan Experience

We conducted another semi-structured interview to evaluate the body scan experience. It included questions concerning the participants' expectations, their physical and psychological comfort and/or discomfort during the body scan and the assessment of their body measures, and about the clarity and transparency of the process. A full version of the questions can be found in the supplementary material of this work.

VR Experience

Regarding the VR experience, we included a variety of VR-specific and task-specific UX measures to get a holistic view of the system's overall UX. We used a combination of qualitative and quantitative measures, in virtuo ratings, and pre- and post-questionnaires for the VR UX evaluation.

Interview We conducted a semi-structured interview with focus on the VR experience. It included questions concerning the participants' expectations and feelings towards the avatar, their favored body weight modification method and the perceived difficulty of the body weight estimation in general, their intensity of body awareness, and their affect towards their body. A full version of the questions can be found in the supplementary material of this work.

Presence We measured the participants' feeling of presence using the Igroup Presence Questionaire (IPQ, Schubert et al., 2001). It captures presence through 14 questions, each rated on a scale from 0 to 6 (*6 = highest presence*). The items are divided into four different dimensions: general presence, spatial presence, involvement, and realism. The questionnaire was provided directly after the VR exposure to capture presence as accurately as possible.

Embodiment As suggested by prior work, we divided the measurements for the feeling of embodiment into VBO and agency (Kilteni et al., 2012). Following Waltemate et al. (2018) and Kalckert and Ehrsson (2012), we presented one embodiment question for each dimension on a scale from 0 to 10 (*10 = highest*). Both questions based on items of the Virtual Embodiment Questionnaire (VEQ, D. Roth & Latoschik, 2020). To investigate possible differences in the feeling of embodiment caused by our interaction methods, the questions were provided multiple times during exposure.

Simulator Sickness To test our system prototype regarding simulator sickness caused by latency jitter or other sources (Stauffert et al., 2018, 2020), we included the Simulator Sickness Questionnaire (SSQ, Bimberg et al., 2020; Kennedy et al., 1993) before and after the VR exposure. It captures the appearance and intensity of 16 different simulator sickness associated symptoms on 4-point Likert scales. The total score of the questionnaire ranges from 0 to 235.62 (*235.62 = strongest*). An increase in the score by 20 between a pre- and post-measurement indicates the occurrence of simulator sickness (Stanney et al., 1997).

Avatar Perception For measuring the affect towards the avatar, we used the revised version of the Uncanny Valley Index (UVI, Ho & MacDorman, 2017), including its four sub-dimensions: humanness, eeriness, spine-tingling, and attractiveness. Each dimension is captured by four to five items ranging from 1 to 7 (*7 = highest*)

Workload We measured workload to (1) determine the perceived effort during the calibration of the system and to (2) determine the perceived difficulty when modifying the avatar's body weight with our modification methods. To capture workload fast and efficiently during VR, we used a single item scale ranging from 0 to 220 (220 = highest) called SEA scale (Eilers et al., 1986), a German version of the Rating Scale Mental Effort (Arnold, 1999; Zijlstra, 1993).

Preference Rankings Participants were asked to order the three body weight modification methods concerning their workload, perceived body weight estimation difficulty, vividness, contentment, and overall preference. Ranking scores were then calculated using weighted scores with reversed weights. A weighting of 4 was used for the highest rank, a weighting of 3 for the second highest, and so on. The overall rankings were summed up and averaged over the number of ratings. A high scores states high workload, difficulty, vividness, contentment, and overall preference.

Calibration and Modification Time To measure the efficiency of the avatar calibration and the interactions methods, we captured the average time needed from the beginning of calibration or modification until the end. Calibration time included potential amendments of the avatar skeleton and re-calibrations. A lower time states a higher efficiency.

Body Image

Body Awareness Similar to VBO, agency, and workload, we included (virtual) body awareness (VBA) as a one-item scale from 0 to 10 (*10 = highest VBA*) assessed at multiple times during exposure. The item was derived from the State Mindfulness Scale (SMS, Tanay & Bernstein, 2013).

Passive Body Weight Estimation (PET) The PET was adapted from prior work (Wolf et al., 2020, 2021, 2022b) and used to capture the participants' ability to numerically estimate the avatars' body weight based on a provided body shape. We repeatedly modified the body weight of the embodied avatar within a range of $\pm 20\,\%$ incremented in $5\,\%$ intervals in a counterbalanced manner resulting in $n = 9$ modifications. To not provide any hints on the modification direction, the HMD was blacked-out during the modification. For each modification, the participants had to estimate the avatar's body weight in kg, which we used to calculate the misestimation M. It is based on the estimated body weight e and the presented body weight of the avatar p as $M = \frac{e-p}{p}$. A negative value states an underestimation, a positive value an overestimation. Additionally, we calculated (1) the average misestimation $\overline{M} = \frac{1}{n} \sum_{k=1}^{n} M_k$ and (2) the absolute average percentage of misestimation as $\overline{A} = \frac{1}{n} \sum_{k=1}^{n} |M_k|$.

Active Body Weight Estimation (AMT) The AMT was inspired by related work (Piryankova et al., 2014a; Thaler et al., 2018a, 2018b) and used to capture the participants' ability to modify the avatar's body weight to match a requested numeric value. We also used it to analyze whether a certain interaction method for body weight modification influenced the participant's ability to judge the avatars' body weight. Participants had to modify the avatar's body weight by using one of our modification interaction methods until they thought it matched a presented numeric target weight in kg. The task was repeated for a target weight range of $\pm 20\,\%$ of the actual avatar's body weight incremented in $5\,\%$ intervals in a counterbalanced manner resulting in $n = 9$ modifications. For each modification, we calculated the misestimation M based on the modified body weight m and the target body weight t as $M = \frac{t-m}{t}$. A negative value states an underestimation, a positive value an overestimation. Additionally, we calculated $\overline{M}$ and $\overline{A}$ as for the PET.

1.4.5 Procedure

The entire evaluation took place in three adjacent rooms (office, body scanner, laboratory) of the University of Würzburg and averaged 117 min. The procedure is illustrated in Figure C1.6.

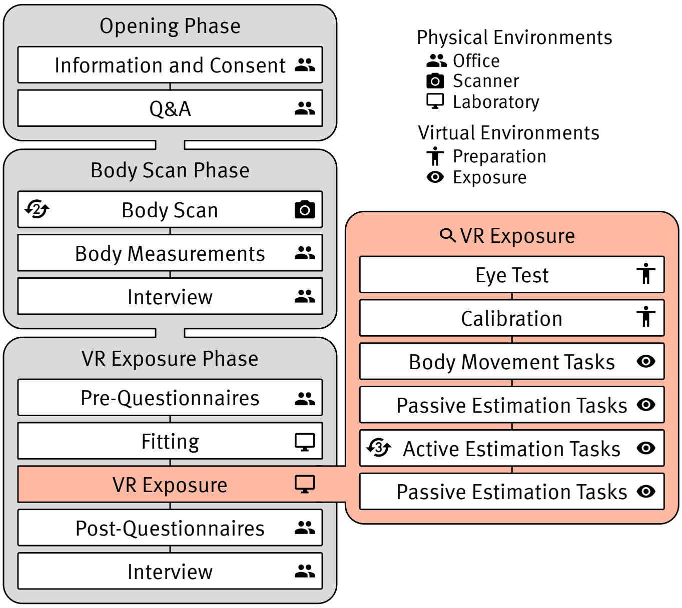

Figure C1.6: The figure provides an overview of the evaluation process as whole (left) and a detailed overview of the VR exposure (right). The icons on the right side of each step show in which physical or virtual environment the step was conducted. The icons on the left side indicate when steps were repeated.

Opening Phase

First, participants were informed about the local COVID-19 regulations, received information about the experiment and the body scans, gave their consent, and generated two personal pseudonymization codes used to store the experimental data and the generated avatars separately. Then, the main experimenter answered potential questions and measured the participant's body height without shoes as required for the body scan.

Body Scan Phase

An auxiliary experimenter performed the body scan in normal clothes without any accessories. Afterwards, the main experimenter measured the interpupillary distance (IPD), body weight, and the participants' waist and hip circumference, and conducted the interview about the scan process. The duration of the interview averaged 4 min. All interviews were recorded by a *Tascam DR-05* voice recorder.

VR Exposure Phase

Prior to the VR exposure, participants answered demographic questions and the SSQ as pre-questionnaires on a dedicated questionnaire computer. Then, an auxiliary experimenter demonstrated the participants how to fit the equipment, adjusted the HMD's IPD, and controlled that all equipment was correctly attached. After finishing the fitting, a pre-programmed experimental procedure was started, and participants were transferred to the preparation environment. For all virtual transitions during the VR exposure, the display was blacked-out for a short moment. All instructions were displayed on an instruction panel and additionally played as pre-recorded voice instructions. As the first preparation step, the participants had to undergo a short reading test to ensure the view was sufficient. Then, they performed the embodiment calibration in T-pose and judged its workload. During the whole VR exposure, participants had to answer questions and measurements verbally. Although interaction between the experimenter and the user may cause small breaks in presence (Putze et al., 2020), we considered this approach as part of the evaluation, since interaction between patient and therapist would also likely occur in clinical settings and advanced in virtuo interaction to answer questionnaires might be difficult for novice users.

After the preparation finished, participants were transferred to the exposition environment. There, they performed five movement tasks in front of a virtual mirror while being instructed to alternatingly look at the mirror and directly on their body to induce the feeling of embodiment. Movement tasks were adapted from related work (Wolf et al., 2020) and had to be performed for 20 s. The first PET followed. Participants estimated the modified body weight of their avatar nine times. Between the estimations, the display was blacked-out briefly to cover the weight changes. In the next phase, participants conducted AMTs nine times for each body weight modification method in a counterbalanced manner. For all body weight estimation tasks, no feedback regarding the estimation error was provided to the participants. The second PET concluded the phase. After each AMT, participants were asked to judge workload, agency, VBO, and VBA in virtuo. The whole VR exposure took 36 min on average. After the VR exposure, participants answered IPQ, SSQ, UVI, and UX questions again on the dedicated questionnaire computer.

Closing and Debriefing Phase

The questionnaires were followed by the second interview about the VR exposure that lasted on average 11 min. At the end of the session, the main experimenter thanked the participants and granted them credits for their participation. As part of the debriefing process after the session, the interviews were first transcribed and then two researchers summarized and clustered the answers into categories.

1.5 Results

In this section, we report the results of our evaluation separated into (1) the body scan experience, (2) the UX of the VR exposure including the different modification methods, and (3) their impact on body image-related measures. The statistical analysis of our results was partially performed using the software *R* for statistical computing version 4.0.5 (R Core Team, 2020) and partially using *SPSS* version 26.0.0.0 (IBM, 2019). All tests were performed against an α of .05.

1.5.1 Body Scan Experience

Feedback on the Body Scanning Process

When asked whether the body scan procedure matched their idea of a body scan, four participants expected a different amount or arrangement of cameras, three participants expected a different scan process (e.g., one camera moving around the body, a laser measuring the body shape, or cameras only in the front), and one participant claimed to have no previous expectations on the body scan process. The other participants stated they already knew the body scan procedure from former experiments and did not remember expectations.

Most of the participants perceived the scan process as simple and clear. Only one participant stated not knowing what was happening between two scans. The experience during the scan process differed from "straightforward" and "easy" ($n = 4$) over "interesting" or "cool" ($n = 4$) to being "something to getting used to" or making one "feel observed" ($n = 4$).

All participants stated positively they would do a body scan again. While most of them did not have suggestions for improvement ($n = 8$). One suggested that the experimenter should be visible during the whole scan process to increase a feeling of safety. Others pointed out that a reduced number of cameras would ease the feeling of being watched and that the stiff posture during the scan felt kind of uneasy after some time.

Feedback on the Body Measurements

When evaluating the assessment of body measures, most participants claimed to perceive it as neutral or similar to being measured during a doctor's appointment ($n = 8$). Some others pointed out they would not expect it in a "normal" lab study but did not perceive it as awkward ($n = 3$). One participant stated to perceive the measuring of their weight as very private and therefore uncomfortable.

1.5.2 VR Experience

Since there was no comparison condition to the overall quantitative scores of the VR experience, we report the data, which were mainly collected on validated and comparable scales, descriptively. For measures captured multiple times during the experience, we calculated the mean value of all data points. The descriptive results of the VR exposure experience are summarized in Table C1.1.

To evaluate the possible occurrence of simulator sickness, we compared SSQ pre- and post-measurements. The observed increase in SSQ scores of 16.21 was below the indication threshold for simulator sickness of 20 points (Stanney et al., 1997), implying a safe use of the application with respect to potential simulator sickness-related impacts. Further, a two-tailed Wilcoxon signed-rank test revealed that the median ranks did not differ significantly between measurements, $Z = 1.14, p = .254$.

Feedback on Embodiment and Avatar Perception

When asked about their feelings towards their personalized avatar, two participants used "neutral" or "okay" to describe their experience, and another four participants described it as "cool", "interesting", or "pleasant". The remaining six participants described the experience as less positive, using words like "strange" and "irritating". While one of the former emphasized

Measure	[Range]	M (SD)
Presence		
IPQ general presence	[0 – 6]	4.58 (0.90)
IPQ spatial presence	[0 – 6]	4.38 (0.95)
IPQ involvement	[0 – 6]	3.75 (0.89)
IPQ realism	[0 – 6]	3.22 (1.2)
Embodiment		
VBO	[0– 10]	5.49 (2.33)
Agency	[0– 10]	7.22 (1.94)
Simulator Sickness		
Pre-SSQ	[0 – 235.62]	26.8 (23.7)
Post-SSQ	[0 – 235.62]	43.01 (39.21)
Avatar Perception		
UVI humanness	[1 – 7]	4.03 (1.10)
UVI eeriness	[1 – 7]	4.06 (0.95)
UVI spine-tingling	[1 – 7]	3.88 (0.88)
UVI attractiveness	[1 – 7]	4.25 (0.87)
Calibration Workload		
SEA	[0 – 220]	20.83 (16.35)
Calibration time in s		96.79 (50.29)

Table C1.1: The table shows the descriptive values for our captured measurements concerning the VR experience. Detailed information regarding the measurements can be found in Section 1.4.4.

the quality of the embodiment compared to other studies, three of the latter criticized the embodiment, especially concerning the lack of facial expression, eye movements and hand gestures. One pointed out that their "hands hold these controllers but the avatar does not". The participants who found the experience rather irritating emphasized a lack of similarity in their avatar's appearance.

The question of whether the avatar's appearance met the participants' expectations also received mixed responses. While one participant found it overall disproportional, six participants stated that the look of their avatar rather met their expectations. The remaining participants indicated that although the avatar's body looked as expected, they did not associate its face with themselves.

Comparison of the Body Weight Modification Methods

For comparing the three AMT conditions (gesture, joystick, and objects), we calculated a one-way repeated-measures ANOVA for each listed measurement (see Table C1.2) except modification times, where we calculated a Friedman test, and preference rankings, which are presented descriptively only. Test results showed significant differences between conditions only for workload, $F(2, 22) = 13.95, p < .001$. Two-tailed paired-sample post-hoc t-tests revealed significant differences in the SEA score between body weight modifications with gesture and joystick, $t(11) = 2.74, p = .019$, gesture and objects, $t(11) = 2.8, p = .017$, and joystick and objects, $t(11) = 4.86, p = .001$. Thus, the workload was considered to be highest when modifying body weight via objects and lowest when using the joystick.

		Gestures	Joystick	Objects	
Measure	[Range]	M (SD)	M (SD)	M (SD)	p
Embodiment					
VBO	[0 – 10]	5.75 (2.63)	5.08 (2.68)	5.38 (2.50)	.300
Agency	[0 – 10]	7.25 (2.61)	7.16 (2.29)	7.33 (2.02)	.915
Workload					
Mod. time in s		23.19 (2.94)	24.53 (10.37)	27.82 (7.72)	.197
SEA	[0 – 220]	41.25 (27.97)	20.75 (13.37)	65.33 (33.06)	$< .001^*$
Preference Rankings					
Workload	[1 – 4]	1.91	2.73	3.45	–
Task difficulty	[1 – 4]	3	1.81	3.36	–
Vividness	[1 – 4]	3.09	3.09	2.27	–
Contentment	[1 – 4]	3.36	3.45	1.91	–
Preference	[1 – 4]	3.27	3.45	2.09	–
Body Awareness					
VBA	[0 – 10]	6.58 (1.98)	7.08 (1.93)	6.67 (2.06)	.053

Table C1.2: The table shows all descriptive values of the measures related to the comparison between our proposed body weight modification methods including p-values when calculated. Asterisks indicate significant p-values. Post-hoc tests for significant differences can be found in the corresponding text.

Feedback on the Body Weight Modification Interaction Methods

When asked to explain their preference for an interaction method, most of the participants who preferred joystick ($n = 8$) stated that it felt most controllable and least complicated. One participant additionally preferred the continuity of joystick-based interaction compared to the necessity of repetition in the gesture-based interaction. The participants who had preferred the gesture-based interaction ($n = 4$) stated they found it most intuitive, flexible, and direct. They reasoned that controlling the speed of modification by extent and speed of arm movements increased usability. None of the participants preferred modification via the objects.

1.5.3 Body Image

In the following, we present the impact of our VR exposure on the body image-related measures of body awareness and body weight estimation as well as the related qualitative feedback.

Comparison of Body Awareness Between Body Weight Modification Interaction Methods

We calculated a one-way repeated-measures ANOVA to compare the body awareness (VBA) during the three AMT conditions (gesture, joystick, and objects). As shown in Table C1.2, VBA ratings differed tendentially between the three AMT conditions, with higher joystick ratings than the other conditions, $F(2, 22) = 3.37, p = .053$.

Feedback on the Intensity of Body Awareness

Seven participants stated they felt in contact with their physical body during the experience, while the other five stated they had lost contact to their body at least once. The latter stated, for example, they focused mainly on the task and the avatar. Others felt that their bodily awareness "got a bit lost" or that the situation and virtual surroundings made them forget reality, including their real body. On the other hand, three participants who stated being aware of their body during the experiment reasoned the embodiment as a main cause. One of them stated that "once before re-calibration, my avatar's foot was kind of crooked, that's when I paid attention to my real body. I made sure my knee was straight". The other one focused on the avatar weight and claimed that "I was still aware of my body, but it was very strange because I was looking at a different mirror image, and sometimes, I felt much heavier when the weight of the avatar was lower than my actual weight". Another reason why participants were aware of their bodily sensations was the physical contact with the floor or the proprioception during movements, which reminded them of their presence in the physical room ($n = 2$).

Feedback on the Affect Towards the Body

Eight of the participants stated that their feelings towards their bodies had changed during the experience. These changes concerned either their general awareness ($n = 3$), their experienced body size ($n = 2$), or their satisfaction with their body ($n = 3$). The two participants stating a change in their experienced body size had either felt thicker or thinner in contrast to their avatar during the experience or felt thinner after the experience. Two of the participants whose bodily satisfaction changed stated an increased body satisfaction or increased motivation to care for their bodily interests. In contrast, one participant reported increased dissatisfaction towards their physical body after the experience.

Feedback on the Perception of Body Weight Changes

Concerning the changes in the avatar's body weight, the participants equally rated them as "interesting" ($n = 6$) or "weird" ($n = 6$). Two participants especially pointed out that it was interesting to compare the avatar's body shape to their own former body, as they had lost or gained weight in the past. One stated "when I started my studies five years ago, I was 20 kg lighter than now, and it was kind of interesting to compare the avatar's look to the memories of my old body shape. It gave me a little perspective on how I want to look". Four of the other participants liked the idea of seeing how they could look if they changed their eating/exercise behavior. Especially the modification towards a lower weight was perceived as threatening by some of the participants ($n = 3$), as they thought it looked a bit unhealthy. To enhance the modification, two participants suggested more individual and fine-grained possibilities to manipulate only body parts instead of the body as a whole, for example, by including "two fixed points on the virtual body, one in the middle of the body and one at the shoulder area, to adjust the weight in these areas more exactly".

Comparison of Body Weight Estimations between Body Weight Modification Interaction Methods

For comparing the performance in body weight estimations between the AMT, we calculated a one-way repeated-measures ANOVA for $\overline{M}$-values, the percentage body weight misestimation, and a Friedman test for $\overline{A}$-values, the absolute percentage body weight misestimation. The tests revealed that the three interaction methods did not differ significantly, neither in $\overline{M}$, $F(2, 22) = 0.66, p = .529$, nor in $\overline{A}$, $\chi^2(2) = 0.50, p = .779$, as summarized in Table C1.3.

	Gestures	Joystick	Objects	
Measure	M (SD)	M (SD)	M (SD)	p
$\overline{M}$ in %	3.44 (9)	3.44 (8.9)	2.41 (8.05)	.529
$\overline{A}$ in %	8.92 (4.58)	8.46 (5.10)	8.36 (3.66)	.780

Table C1.3: The table summarizes the body weight estimation performance (average misestimation $\overline{M}$ and absolute average of misestimation $\overline{A}$) of the comparison between our proposed body weight modification interaction methods.

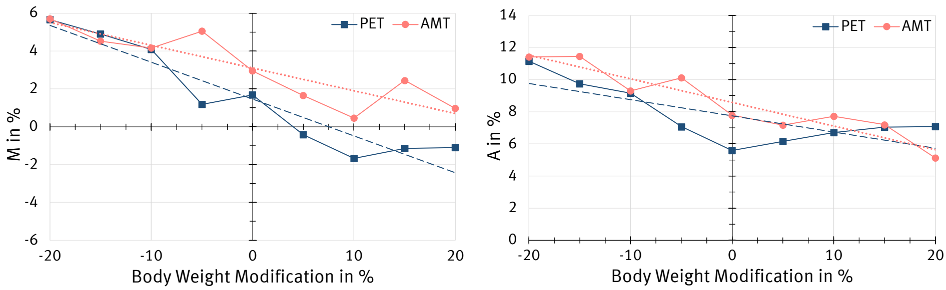

Figure C1.7: The figure shows the body weight misestimations M (left) and absolute body weight misestimations A (right) in relation to the performed body weight modifications for PET and AMT.

Comparison of Body Weight Estimations Between Estimation Methods

We compared AMT and PET using two-tailed paired-samples t-tests for $\overline{M}$-values and two-tailed Wilcoxon signed-rank tests for $\overline{A}$-values. For $\overline{M}$, we showed that participants misestimated the body weight significantly less using the PET ($M = 1.46$, $SD = 8.4$) than when using the AMT ($M = 3.1$, $SD = 8.4$), $t(11) = 2.47, p = .031$. For $\overline{A}$, the median ranks for PET, *Mdn* $= 6.28$, were tendentially lower than the median ranks for AMT, *Mdn* $= 7.85$, $Z = 1.88, p = .060$.

We further analyzed the results of AMT and PET concerning the modification levels ($\pm 20\,\%$ in $5\,\%$ steps) using linear regression. Our data violated pre-requirements for linear regression in terms of homoskedasticity and normality. Therefore, we calculated each linear regression using parameter estimations with robust standard errors (HC4) as recommended by Hayes and Cai (2007). Figure C1.7 shows the body weight misestimations M (left) and the absolute body weight misestimations A (right) for PET and AMT in relation to the modification levels.

For M, the results showed a significant regression equation for PET, $F(1, 106) = 7.88, p = .006$, with a R^2 of .069. The prediction followed the equation M $= -0.194 \cdot$ Body Weight Modification in % $+ 1.462$. The modification level did significantly impact on body weight misestimations M, $t(106) = 5.11, p = .013$. For AMT, we found no significant prediction of the modification level on the body weight misestimations M, $F(1, 106) = 3.05, p = .084$, having a R^2 of .028. The found prediction followed the equation M $= -0.120 \cdot$ Body Weight Modification in % $+ 3.099$. In consequence, the modification level did not significantly impact on body weight misestimations M, $t(106) = -3.46, p = .094$.

For A, the results showed a significant regression equation for PET, $F(1, 106) = 5.27, p = .024$, with a R^2 of .047. The prediction followed the equation A $= -0.101 \cdot$ Body Weight Modification in % $+ 7.743$. The modification level did significantly impact on body weight misestimations A, $t(106) = -2.09, p = .039$. For AMT, we found a significant prediction of the modification level on the body weight misestimations A, $F(1, 106) = 15.7, p < .001$, with a R^2 of .129. The found prediction followed the equation M $= -0.147 \cdot$ Body Weight Modification in % $+ 8.585$. The modification level did significantly impact on body weight misestimations A, $t(106) = -17.9, p < .001$.

In addition to the linear regressions, we averaged body weight estimations for negative and positive modifications for both measurements to analyze differences between the modification directions. Again, we compared AMT and PET using two-tailed paired-samples t-tests for M-values and two-tailed Wilcoxon signed-rank tests for A-values. Test results for M-values showed that body weight misestimations in PET differed significantly between negative ($M = 3.96$, $SD = 11.13$) and positive ($M = -1.09$, $SD = 7.44$) modifications, $t(11) = 2.27, p = .044$, but misestimations in AMT did not differ between negative ($M = 4.86$, $SD = 10.57$) and positive ($M = 1.38$, $SD = 7.45$) modifications, $t(11) = 1.63, p = .131$. For A-values, we found no significant differences between the median negative ranks, *Mdn* $= 7.23$, and the median positive ranks, *Mdn* $= 5.80$, modifications for PET, $Z = 1.26, p = .209$, but found significant differences between the median negative ranks, *Mdn* $= 9.51$, and the median positive ranks, *Mdn* $= 5.39$, modifications for AMT, $Z = 2.59, p = .010$.

Feedback on the Body Weight Estimation Difficulty

Regardless of the estimation method, estimating the body weight of the avatar was found to be difficult ($n = 8$). Only three participants stated they found it relatively easy or only medium-difficult to estimate the body weight. The main reason why participants rated the task as difficult was the high number of repetitions ($n = 2$) or a reduced perceptibility of their physical body, both leading to a “loss of perspective”. Additionally, one participant stated that the task difficulty depended on the distance of the avatar’s weight to their own.

1.6 Discussion

In the present paper, we introduced a prototype of an interactive VR-based system that aims to support body image interventions based on embodied, modulatable, and personalized avatars in future clinically relevant settings. We evaluated the system regarding (1) the body scan experience, (2) the general UX of the VR exposure including body weight modification interaction methods, and (3) the body-image specific UX of the exposure, namely the impact on body awareness and body weight perception. In the following, we summarize and discuss the results of our evaluation to ultimately derive guidelines supporting the design of systems for body image interventions. The guidelines are based on conclusions of the qualitative and quantitative results accomplished by the researchers' observations and participants' comments during the evaluation. While these may overlap with existing best practices or established VR guidelines, we believe it is elementary to summarize them for the given context and to highlight their importance.

1.6.1 Body Scan Experience

Overall, the scan process was mainly rated as simple and interesting, although it took place in a separate room with great technical effort. Participants stated a high acceptance and willingness to be scanned again. In addition, the scan and the associated body measurements were seen as something that one would do in a clinical setting, and that does not trigger unpleasant reservations. This assessment strengthens the idea of using body scans in a clinical context.

Nevertheless, two main criticisms of the scanning process were the feelings of being watched and being left alone. The large number of visible cameras mainly caused the first while both can be attributed to the arrangement of the cameras surrounding the person in all directions. Curtains around the scanner also supported the feeling of being left alone during the scan process. In particular for our target group and the intended clinical usage, amendments seem necessary. Options to reduce the negative feelings could be a change in the arrangement of cameras, e.g., opening the space by placing them only on one side or reducing the number of cameras to a minimum as proposed by Wenninger et al. (2020) and supported by the results of Bartl et al. (2021b). In addition, we suggest a constant dialogue about and during the process to counteract the feeling of being alone.

Guidelines for Body Scanning

1. Users should receive thorough information and instruction in advance about the body scan procedure to provide clarity and transparency.
2. Body scans should be performed unobtrusively to protect privacy and avoid the feeling of being watched.
3. The number and arrangement of cameras should be planned carefully to avoid the feeling of being watched.

4. The number of people involved in the body scan should be minimized to increase privacy, and personal contact should be maximized to increase safety.
5. Body-related measurements should be performed professionally while maintaining privacy.

1.6.2 User Experience of VR Experience

The feedback regarding preparation and calibration was consistently positive, confirming the decision for our approach. This is empirically supported by the low measured calibration times requiring only a short time holding T-pose, and the low workload ratings during the calibration process. Nevertheless, there are further possibilities to reduce the effort for calibration and invasiveness, for example, by using completely markerless body tracking solutions (Wolf et al., 2022b).

Regarding VR-specific measures, participants rated their perceived feeling of presence on an acceptable level (c.f., Buttussi & Chittaro, 2018; Wolf et al., 2020), with lower ratings on involvement and realism. A reason for the lower observed involvement score could be the constant interaction with the experimenter during the tasks (e.g., confirming body weight estimations, rating experiences). Possible implausible content (e.g., body weight modification by interaction) could have impacted negatively on realism. Continuous communication between therapist and patient during weight modifications might be a crucial element in clinical settings. Therefore, further research on the role of presence (and its sub-dimensions) in VR body image interventions seems required, as the latest reviews did not address this topic (Horne et al., 2020; Riva et al., 2019; Turbyne et al., 2021).

Surprisingly, although participants rated their feeling of virtual body ownership descriptively higher compared to non-personalized avatars (Waltemate et al., 2018; Wolf et al., 2020), their ratings were lower than in prior work using personalized and photorealistic avatars (Waltemate et al., 2018). A reason for the noticed differences could be the particularly body-related nature of our task. Avatars created via body scans have a very high resemblance to the individual but still do not provide a perfect visual replica. In a task highly focusing on body perception, even minor inaccuracies may become noticeable, and participants might focus on these, experiencing a diminished feeling of virtual body ownership. Another factor could be the performed body weight modification leading to a reduced congruence between real and virtual bodies and, consequently, might decrease the feeling of virtual body ownership.

The ratings and especially the qualitative statements on avatar perception reveal similar results, as some of the participants stated their avatar to be uncanny or not fully recognizable as themselves. This raises doubts about the degree of personalization of avatars and whether the creation of highly photorealistic textures is currently necessary (and feasible). Tools such as Virtual Caliper (Pujades et al., 2019) can create in shape personalized avatars using only VR equipment. In conjunction with generic avatar generators, such as Meta Human (Epic Games, 2021a), highly realistic avatars with personalized body shapes could be created with less effort. They would not resemble the person perfectly, but this lack of resemblance could make them less uncanny while remaining a still better quality in general. Additionally, a personalization in body shape would be sufficient for simulating body weight changes. However, one counter-argument is provided by Thaler et al. (2018a), who clearly state that the body weight perception of avatars having personalized textures differs from generic ones. To address the question of whether personalization of avatars in our context should be achieved through photorealism or customization, further research seems necessary.

Guidelines for VR Design

1. The physical and mental effort for system calibration should be kept as low as possible.
2. The animations of embodied avatars should be as authentic as possible and include facial expressions, eye movements, and hand gestures to increase realism and reduce eeriness.
3. When using physical controllers, virtual controller representations should be displayed in VR and controlled by the avatar.
4. When using personalized avatars, body shape and texture should aim for the highest possible conformity with the user to reduce uncanniness.

User Experience of Body Weight Modification

When comparing the subjective rankings of the three modification methods, it becomes apparent that the interaction via virtual objects was the least preferred. It was rated as more demanding and difficult, and less vivid, resulting in lower contentment and overall preference than the other two modification methods. Modification via joystick and gestures were rated rather similarly with a slight preference towards the joystick interaction. The in virtuo ratings of workload match these rankings. While joystick was rated quantitatively most positively, the qualitative analysis shows arguments in favor of gesture interaction, especially in terms of vividness and intuitivity. No impact has been noticed on the feeling of embodiment or performance in body weight estimation, which is particularly important in our context.

Regardless of the interaction method, the lack of body weight modification in relation to different body parts (e.g., abdomen, hips, thighs) and in relation to the composition of the body tissue (e.g., fat or muscle mass) was mentioned. The use of advanced body modification methods, such as those presented by Maalin et al. (2020) or Pujades et al. (2019) could allow for body weight modifications that go beyond using only BMI as a single parameter modifying the whole body's weight. However, having more complex body weight modification methods would also increase the complexity of user interaction.

Guidelines for Body Weight Modifications

1. Body weight modifications severely differing from the user's BMI or reaching unrealistic or considered unhealthy ranges should be avoided to reduce alienation.
2. Body weight modifications should allow changing the body weight independently on different body parts considering different body tissue compositions.
3. Body weight modifications performed directly via a hardware input device or body gestures should be preferred over virtual objects or buttons.

1.6.3 Body Image-Related Outcomes

The comparison of body awareness between the three modification methods indicated a higher body awareness in joystick interaction compared to gestures and objects. However, the reported effects of the VR exposure on body awareness and affect towards the body were very individual, with participants reporting either a loss or an increase of body awareness during the experience. Future work with an increased sample size is necessary to further investigate the difference between the conditions and whether the individual differences are related to people's overall body awareness, as proposed by Filippetti and Tsakiris (2017). These insights will be crucial to determine what effects can be expected for a target group with low body awareness or negative body image.

In contrast to body awareness, body weight estimations did not differ between body weight modification methods. However, when comparing the accuracy of the type of estimations task, PET provided more accurate estimates than AMT. While estimating a person's weight based on their appearance is not an everyday task, it is surely more common than actively modifying a (virtual) body to a certain body weight. Thus, the difference might originate in the relative novelty of active modification compared to passive estimation. Another reason could be the different phrasing of the task instructions, which has been shown to have the ability to influence body weight estimation (Piryankova et al., 2014b). For both PET and AMT, the accuracy of the body weight estimation depended on the target weight, or in other words, on the deviation between the own real weight and the virtually presented body weight. This effect has been observed priorly for VR body weight estimation tasks (Thaler et al., 2018a; Wolf et al., 2020) and is in line with the so-called *Contraction bias* as described by K. K. Cornelissen et al. (2015, 2016). It states that body weight estimates are most accurate around an estimator-dependent reference template (of a body) and decrease with increasing BMI difference from this reference. Thereby, bodies heavier than the reference tend to be underestimated, while lighter ones tend to be overestimated. Results on absolute body weight estimations show that although the average misestimations were comparatively low, they are subject to high deviations and uncertainties, which also has been observed priorly (Thaler et al., 2018a). The reasons for this probably lie in the nature of the task, since estimating body weight seems generally challenging, and body image disturbances are ubiquitous even in the healthy population (Longo, 2017). Qualitative feedback confirms the task difficulty. When further analyzing the absolute body weight estimations, it is particularly noticeable that they seem to be easier and more accurate for increased than for reduced body weight. This is rather unexpected since *Weber's Law* suggests that differences in body weight become harder to detect when body weight increases (K. K. Cornelissen et al., 2016). A possible reason for the high uncertainties in the absolute body weight estimations and the contradiction to Weber's law could be the perspective on the avatar offered by the virtual mirror, which mainly shows the front side of the body (P. L. Cornelissen et al., 2018). More research on this topic seems required.

Guidelines for Body Weight Estimations

1. Body weight estimations capturing the current perception of the real body in VR should be performed at the beginning of an intervention, as the perceptibility of the real body might decrease over time.

2. When performing body weight estimations, care should be taken to present the respective body equally from multiple perspectives.

3. When analyzing body weight misestimations based on avatars, determining the average accuracy of the misestimations with healthy individuals helps avoid strong influences of the system properties.

1.6.4 Future Research Directions

The results of our work raise new research questions for future work. First, the high necessity of communication between therapist and user, potentially leading to breaks in presence, raises the question of the general impact of presence in body image interventions. This is also interesting when it comes to augmented reality, as already recognized by Wolf et al. (2022b).

Second, the observed ratings in body ownership despite using photorealistic, personalized avatars and the feedback on avatar perception leads to the question of how photorealism and personalization should be applied to body image interventions. Future work should explore whether avatars that are less personalized in texture are sufficient for our purpose as they might raise less uncanniness.

Third, the severe individual differences in the report of body awareness and affect towards the body raise the question, of which individual characteristics might predict the effects of a VR-based intervention on both variables.

Fourth, future work should further address the difference between active body weight modification and passive body weight estimation we found in this study. It remains unclear which underlying processes lead to differences between the two tasks and whether they impact differently on body image. Similar counts for the observed differences in body weight misestimations for avatars with decreased or increased body weight.

Finally, although our current work is situated in the context of body image disturbances, it aimed to test the usability and user experience of our application regardless of the target population in a non-clinical setting. For subsequent work, we suggest directly incorporating our gained knowledge by considering the participants' feedback and the derived guidelines and testing the system with the intended target population in a feasibility study. To further improve the system in direction of an appropriate clinical setting, technical advancements, like low-cost avatar reconstruction techniques (Bartl et al., 2021b; Wenninger et al., 2020), should be incorporated and domain expert opinions, like recently summarized by Halbig et al. (2022), further considered.

1.6.5 Limitations

Our system implementation and evaluation still have limitations. As stated earlier, some of our participants described mixed feelings toward their personalized avatar and a lack of similarity between their avatar's face and their own. Including animations of facial expressions and eye movements could help increase the association with one's avatar. However, previous work on facial animations has shown only little effect on the perceived embodiment (Döllinger et al., 2022b; Gonzalez-Franco et al., 2020b). Improving the scan quality in the facial area, i.e., by using more cameras in the facial area, could improve this problem.

While modifying the body weight of the personalized avatars, we keep parts of the face region fixed (see Figure C1.3). This does not completely accurately model weight gain/loss in this region, as the soft tissue in this area of the face changes with varying body weight (De Greef et al., 2006). Other methods (Piryankova et al., 2014a; Tang et al., 2021; Zhao et al., 2018) deform the whole face region or regularize the deformation of a region similar to ours (Xiao et al., 2020). These methods, however, produce other undesirable effects such as changing eye socket shape or pupillary distance due to the fact that the underlying statistical model produces one direction of change that is applied to all avatars. As the data measured by De Greef et al. (2006) shows, the soft tissue thickness in our fixed region does positively correlate with BMI. However, we note that the correlation for landmarks in our fixed region is smaller than for those outside the fixed region and as such we decided to keep the face region around the eyes, nose, and mouth fixed. As seen in Figure C1.3, this still produces plausible results while avoiding undesirable changes in face identity. For future work, weight modification models should incorporate information about the underlying bone and muscle structure (Achenbach et al., 2018; Komaritzan et al., 2021) in order to more accurately model changes in soft tissue thickness.

Although our sample included slightly overweight participants, the current design and development phase was limited to students without a diagnosed body image disturbance and predominantly with a BMI in a healthy range. The clinical applicability to our target group, which is already in preparation as part of our ViTraS research project (Döllinger et al., 2019), is one next step after the here presented design and UX optimization phase. Further, given the small sample size of 12 participants and the comparatively narrow range of age, the results cannot be generalized to a wider population. However, the study provides valuable insights into such a system's user experience and facilitates further research.

Overall, the design and development phase would benefit from a larger test sample tailored to the final target group. However, this is not an easy endeavor since it blurs the separation between the usability and user experience tests in the development phases and the clinical application. Hence, it requires closer integration and supervision by therapeutically trained professionals and experts in obesity treatment. Ultimately, this integration would be necessary throughout all steps of technical developments to safeguard against unwanted effects for all participants during the design and development and UX optimization steps. Notably, two participants of our overall healthy sample already showed some emotional reactions when confronted with their modified virtual self. Given the uneasiness some participants felt when their avatar's body weight was modified, further research is needed on how to restrict body weight modifications levels for different populations.

1.7 Conclusion

In this work, we have presented and evaluated the prototype of an advanced VR therapy support system that allows users to embody a rapidly generated, personalized, photorealistic avatar and modulate its body weight in real-time. Our system already offers numerous positive features and qualities, especially regarding the execution of body scans and an overall enjoyable VR experience. The guidelines for designing VR body image therapy support systems that we derived from our results helps to facilitate future developments in this field.

However, more research is needed for a therapeutic application. Possible areas of investigation include the implementation of photorealism, which may need to be revisited when working on body image. More research is also required on the differences between active body weight modification and passive body weight estimation. Finally, investigations with more focus on the target group and the individual characteristics of future users will be necessary, especially concerning body image distortion, body dissatisfaction, and body awareness.

Conflict of Interest Statement

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Data Availability Statement

The raw data supporting the conclusions of this article will be made available by the authors without undue reservation.

Ethics Statement

The studies involving human participants were reviewed and approved by the Ethics Committee of the Institute Human-Computer-Media (MCM) of the University of Würzburg. The participants provided their written informed consent to participate in this study. Written informed consent was obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

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Author Contributions

Nina Döllinger and Erik Wolf jointly conceptualized large parts of the experimental design, collected the data, designed the interaction techniques, and took the lead in writing the manuscript. Nina Döllinger provided the contributions to user experience evaluation and body awareness-related parts and conducted the qualitative data analysis. Erik Wolf provided the contributions on body weight perception and methodology and performed the quantitative data analysis. Erik Wolf and David Mal developed the Unity application, including the experimental environment and avatar animation system. Erik Wolf implemented the interaction techniques for body weight modification. Mario Botsch and Stephan Wenninger provided the framework for the reconstruction of the avatars as well as their integration and realistic body weight modification in Unity. Carolin Wienrich and Marc Erich Latoschik conceived the original project idea, discussed the study design, and supervised the project. All authors continuously provided constructive feedback and helped to shape the study and the corresponding manuscript [7].

[7] The author contributions of the original paper were refined in the course of the dissertation to highlight each author's contribution further.

Supplementary Material

Qualitative Interview Questions

Body Scan Experience

Questions about the body scan:

1. What expectations did you have before the participation about how a body scan would be?
2. Was it clear at any point during the body scan what you had to do?
   a) If not: At what point were there ambiguities and how did they arise?
3. How did you feel about the scanning process?
   a) What was the reason for it?
   b) Were those feelings more pleasant or unpleasant?
4. Would you decide to get your body scanned again?
   a) If not: What is the reasoning behind it?
5. If you could change something about the scanning process, what would it be?
6. Did the gender of the experimenter affect how comfortable/uncomfortable you felt during the scan?
7. Would you have felt differently about the scanning process if you had known the experimenter better?

Questions about the body measurements:

1. How did you feel about the body measurements being taken?
   a) What was the reason for it?
   b) Were those feelings more pleasant or unpleasant?
2. If you could change something about the body measurement process, what would it be?
3. Did the gender of the experimenter affect how comfortable/uncomfortable you felt during the body measurements?

Questions about the body scan and body measurements:

1. What could the experimenter have done to make you feel more comfortable during the scanning and measurement process?

VR Exposure Experience

Questions about the interaction with the embodied virtual human (avatar):

1. How did you feel about the interaction with your personal avatar?
   a) What was the reason for it?
   b) Were those feelings more pleasant or unpleasant?
2. Did the appearance of your avatar meet your expectations?
   a) If not: What would you have expected differently?
   b) If not: Was the deviation from your expectation positive or negative?
3. Did you find it rather easy or rather difficult to estimate the weight of your avatar when it changed without your action?
   a) If difficult: What was the reason for it?
4. Did you find it rather easy or rather difficult to adjust your avatar to the given weight?
   a) If difficult: What was the reason for it?
5. Is there one method of interaction that you would prefer over the others?
   a) What was the reason for it?
6. If you could make something about the interaction with your avatar different, what would it be?

Questions about the (physical) experience:

1. How did it feel for you when the appearance of your personal avatar changed?
   a) Did it feel different when you actively changed the appearance of your personal avatar?
2. Were you aware of your physical body while being embodied to your virtual avatar?
   a) If yes: Were there moments when you paid particular attention to your physical body?
3. Do you had the feeling that interacting with your avatar had an impact on how you felt in your physical body?
   a) If yes: In what ways did you feel changed?
4. Did the interaction with your in body weight changed avatar cause you to perceive or see your own body differently?
   a) If yes: What has changed?

   b) Do you take any direct consequences from this experience?

5. Could you imagine an interaction in which the virtual avatar supports you in experiencing your physical body more consciously?
   a) If yes: How would it look like?

Questions for the instruction of the tasks:

1. What were your expectations about how you would receive instruction within the virtual environment?
2. How did you feel that the instructions for the tasks were given verbally and in text form?
   a) What was the reason for it?
3. Did you notice that there was no visual representation in the form of a speaker or something similar for the verbal instructions?
   a) If yes: Was it rather pleasant or rather unpleasant?
   b) Where in the virtual environment did you locate the instruction?
4. If you imagine a visual representation of the instructing voice, how would it look like?
5. Can you imagine sharing the virtual environment with another person while changing the appearance of your virtual avatar?

Questions about the overall process:

1. If you had the choice - what would you change about the overall process?
   a) Did you notice anything else?

Chapter 2

The Embodiment of Photorealistic Avatars Influences Female Body Weight Perception in Virtual Reality

This chapter has been published as follows:[1]
Wolf, E., Merdan, N., Döllinger, N., Mal, D., Wienrich, C., Botsch, M., & Latoschik, M. E. (2021). The embodiment of photorealistic avatars influences female body weight perception in virtual reality. *2021 IEEE Virtual Reality and 3D User Interfaces (VR)*, 65–74. https://doi.org/10.1109/VR50410.2021.00027x

Figure C2.1: The picture shows the participant's view during the experiment, either only observing (left) or embodying and observing (right) a virtual human. Participants had to guess the body weight of the virtual human.

[1] As part of the dissertation, the published text was editorially revised, with only slight orthographic, stylistic, and formal adjustments, while completely retaining the original semantics.

Abstract

Embodiment and body perception have become important research topics in the field of virtual reality (VR). VR is considered a particularly promising tool to support research and therapy in regard to distorted body weight perception. However, the influence of embodiment on body weight perception has yet to be clarified. To address this gap, we compared body weight perception of 56 female participants of normal weight using a VR application. They either (a) self-embodied a photorealistic, non-personalized virtual human and performed body movements in front of a virtual mirror or (b) only observed the virtual human as other's avatar (or agent) performing the same movements in front of them. Afterward, participants had to estimate the virtual human's body weight. Additionally, we considered the influence of the participants' body mass index (BMI) on the estimations and captured the participants' feelings of presence and embodiment. Participants estimated the body weight of the virtual human as their embodied self-avatars significantly lower compared to participants rating the virtual human as other's avatar. Furthermore, the estimations of body weight were significantly predicted by the participant's BMI with embodiment, but not without. Our results clearly highlight embodiment as an important factor influencing the perception of virtual humans' body weights in VR.

Keywords

Virtual human, presence, virtual body ownership, agency, body image, eating- and body weight disorders

2.1 Introduction

Body weight misperception is an important topic in the domain of body weight disorders (Corno et al., 2018). Researchers have shown that patients suffering from anorexia nervosa perceive their body weight to be higher than it actually is (Mölbert et al., 2017b), while patients suffering from obesity tend to perceive it as lower (Maximova et al., 2008). However, the occurrence of body weight misperception does not necessarily have to be limited to diseases. Recent research indicates that it seems to be an omnipresent part of human perception and cognition (Longo, 2017). In recent years, research has started to address body weight misperception using virtual reality (VR) applications with the idea of systematic modulation of body weight perception using virtual humans (Döllinger et al., 2019). By applying improbable modifications to virtual humans used as digital representations of human bodies, the perception of body weight can be explored in entirely new ways (Thaler, 2019).

Certain potentially influential factors must be considered when designing VR applications that support the research and therapy of body weight misperception. Such factors include the observation perspective on the virtual human (Neyret et al., 2020a; Thaler et al., 2019), its realism and degree of personalization (Piryankova et al., 2014a; Thaler et al., 2018a), and the illusion of being embodied in it (Keizer et al., 2016; Neyret et al., 2020a; Wolf et al., 2020). Research on the influence of these factors has increased recently, leading to a large body of heterogeneous previous work (Wolf et al., 2020). Furthermore, it appears that not only the application characteristics themselves, but also their interplay with the body dimensions of the user can influence body weight estimations in VR. Thaler et al. (2018a) indicated that the body weight estimation of a personalized, non-embodied virtual human observed in VR was affected by the participants' own body mass index (BMI). In our previous work (Wolf et al., 2020), we found a similar effect for female participants embodying a non-personalized virtual human. The lower the participants' BMI, the lower they estimated the embodied virtual humans' body weight and vice versa. We proposed the induced embodiment as an explanation for the revealed effect. However, we have left the comparison of the results to a condition without embodiment to future work.

2.1.1 Contribution

The present study explores the influence of embodiment on body weight perception of a virtual human while keeping the degree of its personalization constant. We systematically extend previous work by comparing body weight estimations between (1) a newly created no embodiment illusion condition and (2) an embodiment illusion condition adapted from Wolf et al. (2020). In the embodiment illusion condition, participants performed five visuomotor tasks while observing the virtual human moving synchronously with the participant's body movements in a virtual mirror. In the no embodiment illusion condition, the virtual mirror was replaced by a door frame leading to an adjacent room in which an animation-controlled virtual human performed the same movements. Therefore, the virtual human could be observed in both conditions from exactly the same allocentric (or third person) perspective, while the egocentric (or first person) perspective was only available in the embodiment illusion condition. After observation, we asked participants for a body weight estimation of the virtual human as our main dependent variable and we checked the perceived feeling of embodiment. We also assessed other potentially mediating variables such as presence, confounding variables such as simulator sickness, and individual-related variables such as body image disturbance or the participant's BMI.

2.2 Related Work

VR has become an important tool for the research of body perception in recent years. By using devices such as head-mounted-displays (HMDs, Sutherland, 1968), users can encounter the feeling of being in a computer-generated artificial world (Burdea & Coiffet, 2003). A resulting subjective reaction to the provided world is called presence. It describes the feeling of really "being" in that virtual world (Skarbez et al., 2017; Slater, 2009). A high feeling of presence is known to cause behavioral, cognitive, and emotional reactions to the presented content of the world that are fundamental for therapeutic scenarios (Diemer et al., 2015; Krijn et al., 2004).

Virtual humans are often an essential part of virtual worlds. When a virtual human refers to a specific user (e.g., is controlled by the user), it can also be called an avatar (Bailenson & Blascovich, 2004). The feeling of being inside an avatar, to own an avatar, and to control an avatar is called illusion of embodiment (Kilteni et al., 2012) and emerged from the essential findings of the rubber hand illusion (Botvinick & Cohen, 1998; IJsselsteijn et al., 2006; Tsakiris & Haggard, 2005). Slater et al. (2010b) expanded this finding to full-body illusions in VR. The illusion leads to an attribution of the virtual human to the self and can be accomplished by achieving sensory coherence of the corresponding sensory inputs. An embodiment illusion's quality is composed of the sub-concepts virtual body ownership (VBO), agency, and self-location (Kilteni et al., 2012). By maintaining a high feeling of those factors, the embodiment illusion's credibility increases and leads to a higher acceptance of the virtual body as the own body, and consequently to an increased feeling of presence (S. Jung & Hughes, 2016; Kilteni et al., 2012; Lugrin et al., 2018; Slater et al., 2010a; Tanaka et al., 2015). The illusion of owning a different virtual body can lead to the Proteus effect. It indicates that the individual's behavior conforms to the expected behaviors and attitudes observed from a virtual (self-)representation (Yee et al., 2009).

In the context of body weight perception, Normand et al. already showed in 2011 in an HMD-based VR environment that full-body illusion with increased belly size can cause differences in the self-assessment of belly size before and after inducing the feeling of embodiment. Piryankova et al. (2014b) could confirm and extend these findings by showing a change in body size perception after embodying an avatar from an egocentric perspective using affordance and body size estimation tasks. Both works show the fundamental efficacy of the modification of body perception through embodiment illusions in VR.

2.2.1 Influences on Body Weight Perception

It is imperative to understand the basic mechanisms of body weight perception inside VR. Notably, most prior work investigating body weight perception with normal weighted participants show a general body weight underestimation of the virtual humans (Nimcharoen et al., 2018; Piryankova et al., 2014a; Thaler et al., 2018a, 2018b, 2019; Wolf et al., 2020). In light of related work, it appears that factors such as the degree of personalization of the virtual human (Thaler et al., 2018a), whether a participant was embodied in the virtual human (Wolf et al., 2020), and the observation perspective on the virtual human (Thaler et al., 2019) contribute to an attribution of the user's self-perception to a present virtual human. By analyzing the relationship between the participant's BMI and the body weight perception of their personalized, non-embodied virtual human, Thaler et al. (2018a) recently found that the participant's BMI serves as a linear predictor for the estimations of the virtual human's body weight. A lower BMI led to an underestimation of the virtual human, while a higher led to an overestimation. For non-personalized avatars, however, the predictive effect of the BMI could not be shown. Interestingly, Wolf et al. (2020) found in a comparable experimental setting that participants who embody a non-personalized avatar also estimated their avatar's body weight in proportion to their BMI. The authors attributed the effect to the induced embodiment and stated that it might have led to a self-attribution of the virtual body and thus to an association of the self with the virtual human. However, the authors left it to future work to compare their findings to a condition with no embodiment illusion.

Another factor that contributes to the feeling of embodiment, and which also could potentially influence body weight perception, is the observer's perspective on a virtual human. In general, we distinguish between two different perspectives. An egocentric perspective, as we experience with our body as human beings, shows only an excerpt of the body from the first-person view. In comparison, an allocentric perspective shows a more holistic picture of a body from a third-person view, for example, by using a (virtual) mirror. In a similar experimental setup to ours, Neyret et al. (2020a) explored the differences in body perception between having an embodied ego- and allocentric perspective and only having an unembodied allocentric perspective. The researchers stated that having only the allocentric perspective allowed the participants to perceive the virtual human without attributing it to themselves. However, the researchers refrained from capturing numeric body weight estimates and from analyzing the influence of the participants' body weight on their measurements. Thaler et al. (2019) investigated the differences between an egocentric and an allocentric perspective on the perception of body weight and body dimensions, but did not induce an illusion of embodiment. Their study did not find a significant influence of the perspective on the perception of body weight or body dimensions, but reported descriptively less accurate estimations for the egocentric perspective. The results support the theory that perspective is not necessarily the most relevant factor influencing body weight perception. Consequently, the authors highlighted in their discussion the potential importance of factors such as the personalization of the virtual human or whether one is embodied to it or not.

2.2.2 Summary

In summary, the aforementioned work suggests that the relationship between the own body and the body of a virtual human is influenced by different self-attribution supporting factors such as the personalization of the virtual human, the illusion of embodiment, or more unlikely the observing perspective. To the best of our knowledge, no previous work has explicitly investigated the influence of embodiment illusions on direct body weight estimations considering the impact of the participant's BMI. Therefore, our work will investigate the influence of an embodiment illusion on the estimation of body weight, while keeping the degree of personalization and the allocentric perspective constant. In doing this, we combine insights of existing work on the effects of embodiment (Keizer et al., 2016; Normand et al., 2011; Piryankova et al., 2014b) and the more recent findings on the influence of the participant's BMI on the perception of body weight (Thaler et al., 2018a; Wolf et al., 2020). Our research thus contributes to the understanding of possible application-related influencing factors and their control within therapy-supporting applications.

2.3 Design and Hypotheses

As noted above, we identified missing research regarding the influence of embodiment on body weight perception of virtual humans in VR. This applies in particular to the influence of the estimator's BMI on the perception of the virtual human's body weight. The exploration of those potential influences defines the primary research goal of our current work. Additionally, we aimed to confirm prior results regarding the influence of embodiment on the feeling of presence and to confirm the illusion of embodiment's influence on the corresponding embodiment measurements VBO and agency. To this end, we used a between-subject design to compare our no embodiment illusion condition with the embodiment illusion condition of Wolf et al. (2020).

2.3.1 Body Weight Perception

Based on the existing literature on body weight perception (Mölbert et al., 2018; Nimcharoen et al., 2018; Piryankova et al., 2014a; Thaler et al., 2018b) and the potentially existing impact of embodiment on body weight estimations (Keizer et al., 2016; Neyret et al., 2020a; Thaler et al., 2018a, 2019; Wolf et al., 2020), we propose the following hypotheses.

Hypotheses

H1.1: Participants in the embodiment illusion condition will estimate the virtual human's body weight lower than in the no embodiment illusion condition.

H1.2: Participants in the no embodiment illusion condition will not misestimate the virtual human's body weight.

H1.3: The BMI of participants in the embodiment illusion condition has a stronger effect on body weight estimation than the BMI of participants in the no embodiment illusion condition.

2.3.2 Presence

With respect to the existing literature on the effects of the illusion of embodiment on presence (S. Jung & Hughes, 2016; Lugrin et al., 2018; Slater et al., 2010a; Tanaka et al., 2015), we propose the following.

Hypothesis

H2.1: Participants in the embodiment illusion condition will report a higher feeling of presence than participants in the no embodiment illusion condition.

2.3.3 Embodiment

Regarding the embodiment measurements used to check for our manipulation strength between the no embodiment and the embodiment illusion condition, we propose the following hypotheses based on the existing literature (Kilteni et al., 2012; D. Roth & Latoschik, 2020).

Hypotheses

H3.1: Participants in the embodiment illusion condition will report a higher feeling of VBO towards the virtual human than participants in the no embodiment illusion condition.

H3.2: Participants in the embodiment illusion condition will report a higher feeling of agency towards the virtual human than participants in the no embodiment illusion condition.

2.4 Apparatus

The system we used was adapted from Wolf et al. (2020) and implemented using *Unity* 2019.1.10f1 (Unity Technologies, 2019). The following sections will summarize the adopted system parts and describe the applied adaptions. A more detailed description of the whole system architecture as well as the detailed design decisions can be found in the corresponding work. The VR hardware setup consisted of four *SteamVR Base Stations 2.0*, a *HTC Vive Pro HMD*, two *HTC Vive Controllers*, and three *HTC Vive Trackers 2.0* (HTC, 2018a). It was integrated using *SteamVR* version 1.13.9 (Valve, 2020b) and its corresponding Unity plug-in version 2.5.0 [2]. The HTC Vive Pro provides a resolution of 1440×1600 px per eye, a field of view of $110°$, and a refresh rate of 90 Hz. Software and VR hardware were driven by a modern VR-capable gaming PC (*Intel Core i7-9700K, Nvidia RTX2080 Ti, 32GB RAM*) running *Windows 10*. The motion-to-photon latency of the setup measured with a *Casio EX-ZR200* high-speed camera recording 240 fps averaged 50 ms as determined by frame-counting (He et al., 2000).

2.4.1 Virtual Environment

Using *Blender* version 2.79b (Blender Foundation, 2019), we adopted the already existing realistic looking VE (Eckstein et al., 2019; Wolf et al., 2020) to fit the needs of the no embodiment illusion condition. To this end, we added a door frame leading into a mirrored, adjacent room in which we placed an agent to allow for a similar allocentric perspective on the virtual human as in the embodiment illusion condition. For the embodiment illusion condition, Wolf et al. (2020) used a virtual full-body mirror to enable participants to observe their virtual human from an allocentric view [3]. The modifications are depicted in Figure C2.1 (left and right).

2.4.2 Virtual Human

To ensure comparability with Wolf et al. (2020), we used the same virtual human created by scanning a female model with a BMI of 22.25, a body height of 1.68 m, and a body weight of 62.8 kg. Following their design, the virtual human was used for all participants and was uniformly scaled to match the participants' body height. The scaling was necessary to assure the virtual human in the embodiment condition matched the participant's body height.

[2] https://assetstore.unity.com/packages/tools/integration/steamvr-plugin-32647

[3] https://assetstore.unity.com/packages/tools/particles-effects/magic-mirror-pro-recursive-edition-103687

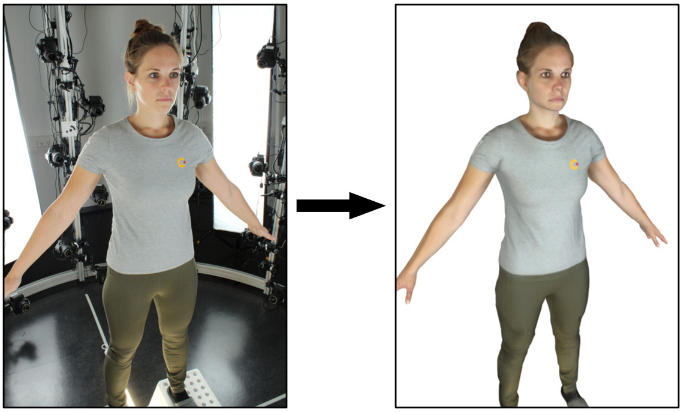

Figure C2.2: The figure from Wolf et al. (2020) shows one of the images taken from the model of the virtual human during the body scan (left) and her generated representation (right).

Consequently, we also had to scale it in the no embodiment condition to control between conditions. Figure C2.2 shows a picture of the model (left) and her generated virtual human (right) from the same perspective.

2.4.3 No Embodiment Illusion

In the no embodiment illusion condition, participants stood in front of the virtual human within the VE. The virtual human was located behind a virtual door frame, leading to a separate, mirrored room comparable to the one in which the participants were virtually located. A screenshot of the participant's view is shown in Figure C2.1 (left). The virtual human could only be observed from an allocentric perspective while it performed pre-recorded body movements completely decoupled from the participant's movements. Thus, the participants in the no embodiment illusion condition had no egocentric perspective on the virtual human. We used the same system as the embodiment illusion condition to capture the movements used to animate the virtual human. A female actor performed all movements according to the description in Section 2.5.3 and the animations were recorded using the Animation Baker provided by the Unity plug-in *FinalIK* version 1.9 [4]. We did not perform post-processing on the animations to provide an identical movement quality between the conditions. Animations were played using Unity's animation system and controlled by a custom agent script during the experiment.

[4]https://assetstore.unity.com/packages/tools/animation/final-ik-14290

2.4.4 Embodiment Illusion

The embodiment illusion condition was completely adopted from Wolf et al. (2020). In the following, we summarize the implementation. Participants embodied the generated virtual human as an avatar within the VE. The participants' movements were captured by the prior described SteamVR setup. FinalIK version 1.9 was then used to continuously compute a body pose and animate the participants' avatar in real-time to support visuomotor coupling and induce the feeling of embodiment. Participants could observe themselves from an allocentric perspective by looking into a virtual mirror added to the scene. They could also observe their avatars' virtual body from an egocentric perspective. The virtual presentation remained the same distance to the participants in both conditions. A screenshot of the participant's view is shown in Figure C2.1 (right).

2.5 Evaluation

The following section will describe our performed experiment. Measurements, body movements, and the experimental procedure were adopted from Wolf et al. (2020) and adapted for our purpose.

2.5.1 Participants

A total of 56 females participated in our study, 49 of whom were undergraduate students at the University of Würzburg and received course credit for participation. Seven further participants were post-graduates on a voluntary basis. While body weight misperception is subject to gender-specific differences (Connor-Greene, 1988; Hsu, 1989; Paeratakul et al., 2002), and to increase the comparability to the related work, we used data only from female participants. Prior to our experiment, we defined the following exclusion criteria: (a) participants should have correct or corrected-to-normal vision and hearing; (b) participants should have at least ten years of experience with the local language; (c) participants should not have suffered from any kind of mental or psychosomatic diseases such as eating or body weight disorders; (d) participants should have a BMI above 17 and below 30; and (e) participants should not have a known sensitivity to simulator sickness. Three participants met the exclusion criteria, and another one was excluded due to technical issues, leaving 26 participants in each condition.

2.5.2 Measurements

Body Weight Measurements

We used the participants' *body weight misestimation (BWM)* of the virtual human as a dependent variable and the *BMI difference* between participants' BMI and the scaled virtual humans' BMI as a body weight-related control variable. Wolf et al. (2020) showed that BMI difference is a major predictor for estimating the virtual human's body weight. For calculating these measurements, we captured the body weight and height of the virtual human's model and of the participants with officially approved and calibrated medical equipment. Additionally, we asked participants to estimate the virtual human's body weight. In the following, we will summarize the calculation of the measurements. A more detailed explanation can also be found in the work of Wolf et al. (2020).

BWM is based on the relative difference between the virtual human's BMI, estimated by the participants E-BMI and the approximated virtual human's BMI (A-BMI), and is calculated as $\frac{(\text{E-BMI}-\text{A-BMI})}{\text{A-BMI}}$. A negative value of the BWM represents an underestimation of the virtual human's body weight, and a positive value an overestimation. The E-BMI was calculated using its estimated body weight and the virtual human's body height in the standard BMI calculation equation $\frac{\text{Body Weight in kg}}{(\text{Body Height in m})^2}$. The A-BMI was approximated by multiplying the previously identified scaling factor of the virtual human with the model's BMI. The scaling factor s was calculated by dividing the participant's body height by the height of the virtual humans' model. The scaling approach we used in our work only approximates the virtual human's BMI and results in smaller participants facing a relatively lighter avatar and larger participants facing a heavier one. Therefore, we included the scaling factor as a control variable in our results. The BMI difference between the participant's BMI (P-BMI) and the virtual human's approximated BMI is calculated as $\frac{(\text{P-BMI}-\text{A-BMI})}{\text{A-BMI}}$. A negative or positive value indicates that the participant was lighter or heavier than the virtual human.

Presence Measurements

We captured presence by a *one-item in virtuo question* (Bouchard et al., 2004, 2008) and by the *Igroup Presence Questionaire* (IPQ, Schubert et al., 2001). The one-item question is considered a rapid and accurate presence measurement and asks participants to state on a scale between 0 and 10 (*10 = highest presence*) how present they currently feel in the virtual environment. Additionally, we used the IPQ to measure presence more conclusively and reliable post-immersion (Bouchard et al., 2004). It captures presence through 14 questions divided into four different dimensions, general presence (GP), spatial presence (SP), involvement (INV), and realism (REAL), reported on a normalized scale from 0 to 10 (*10 = highest presence*).

Embodiment Measurements

We captured two embodiment sub-categories, virtual body ownership (VBO) and agency (AG), each by *a one-item in virtuo question* (Kalckert & Ehrsson, 2012; Waltemate et al., 2018) and by the *Virtual Embodiment Questionnaire* (VEQ, D. Roth & Latoschik, 2020). In the in virtuo questions, participants had to state on a scale from 0 to 10 (*10 = highest VBO, AG*) to what extent they felt that the virtual human's body was their body and to what extent they felt the virtual body moved as they intended it to move. Additionally, we used the VEQ to measure VBO and AG post-immersion. The questionnaire assesses four items for each dimension, reported on a normalized scale from 0 to 10 (*10 = highest VBO, AG*).

Control Measurements

Body weight misperception is known to have a strong relationship to self-esteem and attitude towards the body (Cooper et al., 1987; Schwartz & Brownell, 2004). Therefore, we controlled self-esteem and body shape concerns as further potentially confounding factors between conditions. For self-esteem, we used the Rosenberg self-esteem scale (RSES, Ferring & Filipp, 1996; Rosenberg, 2015; M. Roth et al., 2008) to capture self-esteem on a scale between 0 and 30 (*30 = high self-esteem*). For body shape concerns, we used the validated shortened form of the body shape questionnaire (BSQ, Cooper et al., 1987; Evans & Dolan, 1993; Pook et al., 2002). The score is captured with 16 different items ranging from 0 to 204 (*204 = highest concerns*). As another potentially confounding factor, we captured the feeling of simulator sickness by use of the simulator sickness questionnaire (SSQ, Kennedy et al., 1993). It captures the presence and intensity of 32 different symptoms associated with simulator sickness. The total score of the questionnaire ranges from 0 to 2438 (*2438 = strongest simulator sickness*). An increase in the score between a pre- and post-measurement indicates the occurrence of simulator sickness.

2.5.3 Body Movements

The following five body movements were used either to animate the virtual human in the no embodiment illusion condition or as movement tasks in the embodiment illusion condition. All movements were guided by instructions to either watch or perform the movements carefully.

Figure C2.3: The figure shows a participant who is currently performing BM4. The corresponding egocentric view is depicted in Figure C2.1 (right).

Body Movements

BM1: Raising the right hand and relaxed waving straight ahead.
BM2: Raising the left hand and relaxed waving straight ahead.
BM3: Walking in place with knees up to the height of the hip.
BM4: Stretching out both arms straight ahead of the body and moving them in a circle.
BM5: Stretching the arms to the left and right and moving the hips alternately to the left and right sides.

In the embodiment illusion condition, the following sentence accompanied each body movement instruction to support visuomotor stimulation: "Please look alternately at the movements of your mirror image and your body." In the no embodiment illusion condition, each body movement introduction was followed by the sentence: "Please observe the movements and the posture of the virtual human carefully so that you can repeat them later". Figure C2.3 shows a participant currently performing BM4.

2.5.4 Procedure

Our participants were each tested in individual sessions with an average duration of 35 min. For a better understanding, the whole experimental procedure is visualized in Figure C2.4. During each session, explicit attention was paid to compliance with local hygiene and safety regulations regarding COVID-19 valid at the time of the experiment (i.e., wearing masks, continuous air circulation, equipment disinfection, keeping distance).

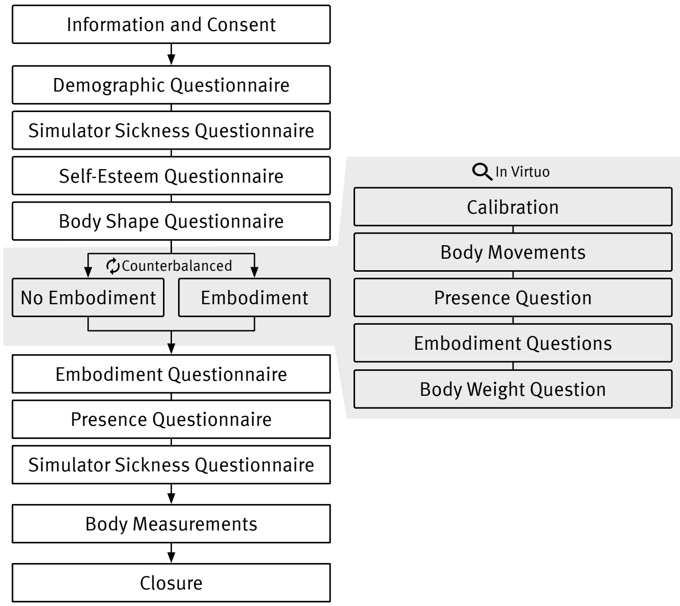

Figure C2.4: The flowchart visualizes the controlled experimental procedure and gives an overview of the performed measurements.

Information, Consent, and Pre-Survey

Participants first had to read the experimental information and gave consent. Afterward, they answered the pre-questionnaires using LimeSurvey 3 (LimeSurvey GmbH, 2019). The questionnaires were either translated to German as precisely as possible by us, or were validated, translated versions.

Calibration and Exposure

After the pre-questionnaires, the exposure phase in VR followed. The experimenter demonstrated how to fit the equipment using a demonstration device and visually checked that the participant used theirs correctly. For this reason, participants also were asked to adjust the HMD's interpupillary distance and position on the head until they could read a sample text in VR. Subsequently, the exposure phase started following a pre-programmed linear procedure (see Figure C2.4, right) that automatically played pre-recorded auditory instructions and displayed text instructions for calibration, body movements, and in virtuo questions. For calibration, participants stood briefly in a T-Pose. Participants were explicitly told that the virtual human they were to face was scaled to their exact body height (for both conditions) and that it either represented another person (for the no embodiment condition) or themselves (for the embodiment condition). In the no embodiment condition, participants were additionally told that the person in the adjacent room performing loosening exercises should be observed carefully. After calibration, participants performed or observed each of the body movements for 34 sec. The virtual human was only visible to the participants when they had to perform or observe body movements. Otherwise, the mirror or the door-frame was blackened. Finally, participants verbally answered the in virtuo questions regarding presence and embodiment, and estimated the virtual human's body weight (in kg). The experimenter recorded verbal responses within the experimental software. The whole exposure phase in VR lasted on average 7.6 min.

Post-Survey and Body Measurements

After the exposure phase, participants continued with the questionnaires and the body measurements were performed. For the exposure phase and the body measurements, participants had to take off their shoes to ensure a correct body height measurement.

2.6 Results

Statistical analysis was performed using the software *R* for statistical computing version 4.0.5. (R Core Team, 2020). For power analysis, we used *G*Power* version 3.1.9.7 (Faul et al., 2009). The descriptive results of our evaluation are shown in Table C2.1. For greater comparison between the different measurements, we normalized all variables' values, with the exception of BWM, to a range between 0 and 10. Before we conducted the main analysis, we performed a test of normality and homogeneity of variances for all variables to determine whether the data met the parametric testing requirements. For body weight perception, the BWM data

Measure	No Embodiment M (SD)	Embodiment M (SD)
Body Weight Perception		
BWM in %	0.53 (6.00)	−3.25 (8.81)
Presence		
IV	7.46 (1.27)	6.69 (1.54)
IPQ G	2.69 (1.64)	7.05 (2.02)
IPQ SP	5.23 (1.19)	7.12 (1.18)
IPQ INV	3.11 (1.58)	4.58 (1.93)
IPQ REAL	4.09 (0.86)	4.68 (1.39)
IPQ Total	4.17 (1.27)	5.84 (1.17)
Embodiment		
IV VBO	1.73 (2.29)	4.77 (2.12)
IV AG	2.58 (2.61)	8.04 (1.40)
VEQ VBO	4.46 (1.73)	5.29 (2.02)
VEQ AG	5.63 (1.60)	8.28 (0.91)

Table C2.1: The table shows the descriptive values for our captured variables normalized from 0 to 10 except BWM.

met the criteria for parametric testing. To test our hypotheses on BWM, we calculated a multiple linear regression model. We included the centered BMI difference and the condition as predictors in our regression model. To test whether the deviation between participants' body weight estimations and the virtual humans' actual body weight differed between the two conditions (H1.1), we analyzed the main effect of the condition on BWM within the regression model. To test whether participants misestimated the avatar's weight in the no embodiment illusion condition (H1.2), we included an additional two-sided, one-sample t-test. As we expected no misestimation in this condition, we decided to control the probability of false-positive test results by adjusting the alpha level to $\alpha = .20$. To test the interaction between participants' BMI difference and condition in predicting BWM (H1.3), we analyzed the interaction effect of the regression model. All hypotheses within the linear model were tested against a non-adjusted α of .05.

Concerning presence and embodiment, the pre-assumptions for parametric testing were violated in some cases. Thus, we conducted one-sided Mann-Whitney-Wilcoxon tests with effect size r for those measurements (H2.1, H3.1, H3.2). As both measures included several sub-scales resulting in a total of 11 tests, we adjusted the p-values using Bonferroni-Holm correction. The adjusted p-values were tested against an α of .05. In case of non-significant results, we calculated sensitivity analyses using G*Power to support our interpretation.

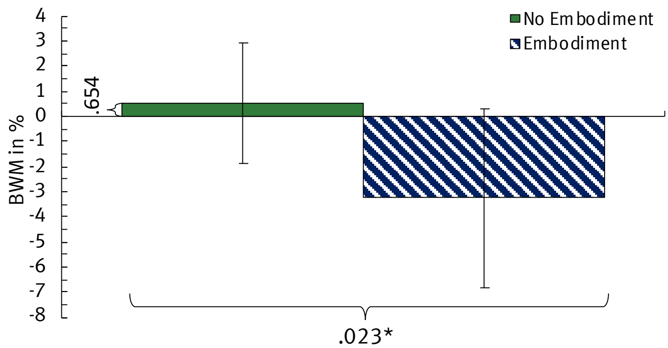

Figure C2.5: The chart shows the BWM for the no embodiment and embodiment illusion conditions together with the corresponding p-values. Error bars represent 95 % confidence intervals. Asterisks indicate significant p-values.

2.6.1 Body Weight Perception

In line with our expectations, a significant regression equation was found, $F(3, 48) = 8.67, p < .001$, with an R^2 of .31. The prediction followed the equation BWM $= -3.59 + 0.55 \cdot$ BMI difference $+ 4.17 \cdot$ condition $- 0.48 \cdot$ (BMI difference $\cdot$ condition) (For condition: embodiment illusion = 0, no embodiment illusion = 1). As expected (H1.1), within this regression model, the experimental condition had a significant main effect on BWM, $t(48) = 2.35, p = 0.023, \beta = 0.27$. The additional t-test (H1.2) revealed that the participants' estimation in the no embodiment illusion condition did not deviate significantly from the avatar's approximated body weight, $t(25) = 0.45, p = .654, d = 0.089$. A sensitivity analysis revealed that a t-test with the adjusted α of .20 and the sample size of 26 participants would have revealed relatively small effects of $d = 0.423$ or greater with a power of .80 (Cohen, 2013). Thus, we accepted H1.1 as confirmed and did not reject H1.2. The results are shown in Figure C2.5.

Additionally to the main effect of the condition, the regression model revealed a significant impact of the participants' BMI, $t(48) = 4.56, p < .001, \beta = 0.50$ on the BWM. In line with our expectations (H1.3), we found a significant interaction between BMI difference and condition, $t(48) = -3.18, p = .003, \beta = 0.39$. Thus, the slope of the regression of BMI difference on BWM was affected significantly by the condition. The resulting interaction is depicted in Figure C2.6. While in the condition with full body illusion the BWM is related to the BMI difference, in the condition without body illusion, the relationship between BMI difference and BWM is negligible. Thus, H1.3 was confirmed.

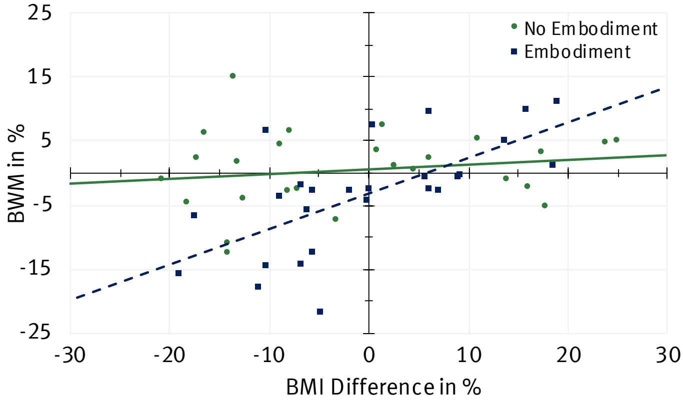

Figure C2.6: The chart shows the BWM for each of our conditions depending on the BMI difference between the participants' BMI and the virtual humans' BMI.

2.6.2 Presence

Contrary to our hypothesis H2.1, the in virtuo presence question did not differ significantly between the two conditions, $U(26, 26) = 229.5, p_{adj.} = .980$. However, the post-experience presence score revealed a significant difference between the conditions with medium to large effect sizes. Participants reported a higher general presence experience (IPQ G), $U(26, 26) = 627.5, p_{adj.} < .001, r = 0.76$, a higher level of involvement (IPQ INV), $U(26, 26) = 486.5, p_{adj.} = .016, r = 0.38$, and a higher level of spatial presence (IPQ SP), $U(26, 26) = 583.5, p_{adj.} < .001, r = 0.62$, in the embodiment illusion condition compared to the no embodiment illusion condition. In line with these results, the total presence score was higher in the condition with embodiment illusion (IPQ Total), $U(26, 26) = 560.5, p_{adj.} < .001, r = 0.57$. The rating of the environment's realism (IPQ REAL) did not differ significantly between the conditions, $U(26, 26) = 418.5, p_{adj.} = .070$. A sensitivity analysis revealed that on an α-level of .05, a one-sided Mann-Whitney-Wilcoxon test with a group size of $n = 26$ would only have detected medium effects (Cohen, 2013) with an effect size of $r = 0.34$ and more with a power of .80. Consequently, we cannot completely discard a small effect of the condition on the perceived realism. The results are depicted in Figure C2.7. We accepted H2.1 as mainly confirmed.

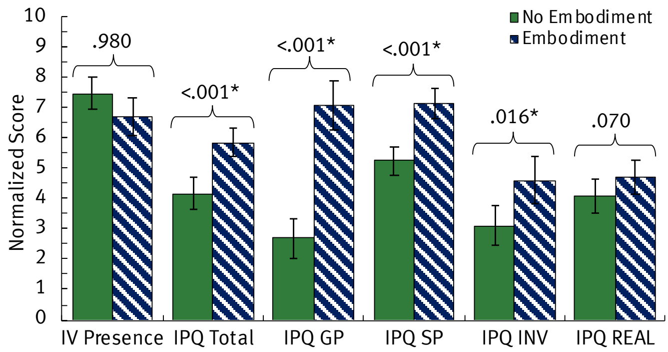

Figure C2.7: The chart shows the average normalized presence scores for the no embodiment and the embodiment illusion condition together with the corresponding p-values. Error bars represent 95 % confidence intervals. Asterisks indicate significant p-values.

2.6.3 Embodiment

In line with H3.1, the in virtuo measure of VBO revealed a significant difference between the conditions, $U(26, 26) = 568, p_{adj.} < .001, r = 0.59$, with participants reporting a higher feeling of VBO in the embodiment illusion condition compared to the no embodiment illusion condition. However, the post-experience ratings on VBO (VEQ VBO) did not differ significantly between the conditions, $U(26, 26) = 401, p_{adj.} = .377$. Again, on an α-level of .05, a one-sided Mann-Whitney-Wilcoxon test with a group size of $n = 26$ would have detected medium effects of at least $r = 0.34$ with a power of .8. The ratings of agency (H3.2) within and after the virtual experience revealed a clear effect. Both

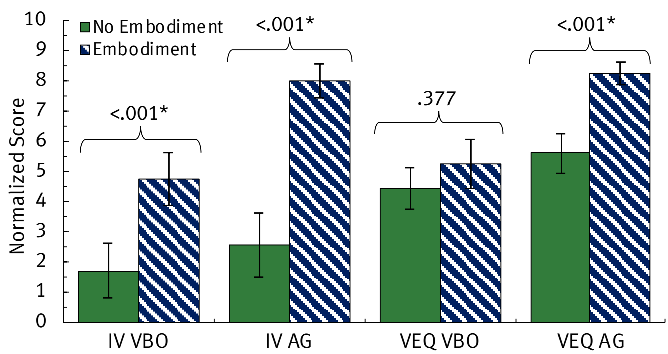

Figure C2.8: The chart shows the average normalized embodiment scores for the no embodiment illusion and the embodiment illusion condition including corresponding p-values. Error bars represent 95 % confidence intervals. Asterisks indicate significant p-values.

	No Embodiment		Embodiment		
Measure	Range	M (SD)	Range	M (SD)	p
Scale s	0.94–1.05	0.99 (0.03)	0.93–1.10	0.99 (0.04)	.921
BMI	17.4–27	21.8 (3)	17.2–27.2	22 (2.2)	.757
RSES	13–29	22.5 (5)	9–30	23.1 (4.7)	.650
BSQ	36–157	91.1 (33.5)	40–148	79.5 (26.8)	.174

Table C2.2: The table shows the results of the control variables scaling factor (s), BMI, self-esteem (RSES), and body shape concerns (BSQ).

in virtuo, $U(26, 26) = 659.5, p_{adj.} < .001, r = 0.83$, and post-experience (VEQ AG), $U(26, 26) = 623.5, p_{adj.} < .001, r = 0.73$, the embodiment illusion condition led to a significantly higher reported feeling of agency than the no embodiment illusion condition. Thus, H3.1 was only confirmed partially, while we accepted H3.2 as fully confirmed. The results are depicted in Figure C2.8.

2.6.4 Controls

No participants were excluded due to rising simulator sickness during the experiment. An overview of the participants' demographic data and control variables can be found in Table C2.2. To test whether the scaling factor s influenced our results on body weight perception, we performed a moderation analysis including BMI difference and condition as predictor variables and the scaling factor as a moderator variable. The scaling factor had a significant impact on the BWM $t(45) = -2.5, p = .016$. However, neither the interaction between the scaling factor and the BMI difference, $t(45) = 0.88, p = .400$, nor the interaction between the scaling factor and the condition, $t(45) = -0.10, p = .919$, was found to be significant. These results identify the scaling factor as a non-moderator of the relationship between the BMI difference, the embodiment illusion condition, and BWM.

2.7 Discussion

The purpose of this work was to investigate the influence of self-embodying a virtual human in VR on the perception of the body weight of a photorealistic virtual human, the participants' feeling of presence, and the participants' feeling of embodiment. However, the latter was primarily recorded to verify our successful manipulation between our no embodiment illusion and the embodiment illusion condition of Wolf et al. (2020). Additionally, we considered the BMI difference between the participants' BMI and the virtual humans' BMI on body weight estimations as a potentially major moderating factor. In general, our results show that having an embodiment illusion has a significant influence on body weight estimation, including the moderating influence of the BMI difference, on the feeling of presence, and on the feeling of embodiment.

2.7.1 Body Weight Perception

Among other potential factors, we identified the presence or absence of an embodied virtual human as potential influencing factor on body weight perception. Prior work suggested that embodiment might contribute to an attribution of one's own body weight to the perception of a virtual human's body weight and would lead to the underestimation of the virtual human by a sample within a healthy BMI range. Therefore, we hypothesized that body weight estimations of the virtual human in the embodiment illusion condition will be significantly lower than in the no embodiment illusion condition (H1.1), which we could confirm with our results. Additionally, we did not reject our hypothesis that body weight estimations in the no embodiment illusion condition would not significantly differ from the virtual human's body weight (H1.2). We further hypothesized that our condition would moderate the effect of BMI difference between the participants' BMI and the virtual humans' BMI on body weight estimations (H1.3). We confirmed this hypothesis, as we observed no significant predictive influence of BMI difference on BWM in the no embodiment illusion condition, while in the embodiment illusion condition, body weight estimations were highly significant predicted by the BMI difference.

Our results on body weight perception are in line with the presented related work and with our hypotheses. The confirmation clearly highlights the role of embodiment and one's own body weight in the perception of a virtual human's body weight. Our results indicate that (a) the body weight of our non-personalized virtual human is more realistically perceived when observed without the embodiment illusion. Thus, we claim that the body weight perception of the virtual human was not influenced by the VR system itself. We further showed that (b) the embodiment illusion impacts the perception of non-personalized humanoid virtual humans' body weight. We were also able to show (c) that embodying the virtual human impacts the relationship between one's own BMI and the weight perception of the virtual human, leading to a more biased estimation with an increased difference between one's own and the virtual human's BMI.

The results of our work and of prior related work (Thaler et al., 2018a; Wolf et al., 2020) suggest that embodiment and the degree of personalization are factors contributing to an attribution or projection of one's own body perception to the perception of a virtual human. However, with our experimental design, we could only show that the feeling of embodiment influences the body weight perception of virtual humans. We suggest performing an additional experiment considering the impact of embodiment on BWM with regard to the degree of personalization in order to further explore those factors. Moreover, it seems necessary to explore other potential factors that could moderate virtual humans' body weight perception (e.g., avatar appearance (Yee & Bailenson, 2007) or situational cues (Peña et al., 2009)). It also raises the question of whether other body or mental properties exist that moderate the perception of a virtual human when feeling related to it (e.g., self-similarity).

It has yet to be clarified by which factors the aforementioned attribution or projection is exactly influenced. The effect discovered, however, raises the question of whether our perception can also be influenced reciprocally by a virtual human displaying high identity conformity with the user, through, for example, personalization or by an embodiment illusion. Corresponding studies without the use of photorealistic virtual humans and accurate body weight estimations (Keizer et al., 2016; Neyret et al., 2020a; Normand et al., 2011; Piryankova et al., 2014b), as well as research on the Proteus effect (Ratan et al., 2020; Yee et al., 2009), support the assumption that the user's body weight perception can be affected by the virtual humans appearance. Therefore, future work should further focus on investigating the interplay between one's own body weight perception and the suggested properties of virtual humans. For this purpose, it seems reasonable to compare the perception of one's own body size before and after the exposure (Keizer et al., 2016) and to put these results in relation to the perception of the virtual human. A clear limitation regarding the absolute body weight perception concerns the approach of uniform virtual human scaling, which was mainly used in our work to maintain comparability with Wolf et al. (2020). We could show that the scaling of the virtual human influenced the estimation of body weight in our two conditions but did not differ between them. Although the absolute estimates were slightly affected by the approximation of the virtual human's BMI, it had no effect on the comparisons between the conditions nor on the effects discovered. Nevertheless, future research should aim to use more realistic scaling approaches, for example, by using statistically trained mesh deformation models (Piryankova et al., 2014a), which could also be used to modify the body weight of the virtual humans. Such models also provide the basis for research on body weight perception of personalized virtual humans and allow multiple estimations based on only one repeatedly modified virtual human.

2.7.2 Presence and Embodiment

Regarding presence, we hypothesized that participants in the embodiment illusion condition will report a significantly higher feeling of presence than participants in the no embodiment illusion condition (H2.1). While the scores of the IPQ significantly supported our assumption, the in virtuo presence did not differ significantly between the two conditions. Therefore, we mainly confirm our hypothesis. When looking at our results, the reliability and validity of single-item measurements for presence might be questioned in order to explain the inconsistency within the results. A single-item measure does not address all the different subtleties of presence as noticed already by other researchers (Wanous & Hudy, 2001) and suggests using full questionnaires in virtuo as recommended by recent research (Schwind et al., 2019). Our results also show the difficulties of presence's subjective assessment and underline the importance of more objective measurements in research (Slater, 2004).

For embodiment, we measured VBO and agency with two in vitro embodiment questions and the VEQ to assess the strength of our experimental manipulation between conditions. Consequently, we expected higher values in VBO (H3.1) and agency (H3.2) in the embodiment illusion condition compared to the no embodiment illusion condition. For VBO, we could show significantly higher scores in the in virtuo question but no significant difference for VBO in the VEQ. Regarding agency, we positively support our hypothesis (H3.2) as participants reported a significantly higher agency in both measurements. In general, we consider our embodiment manipulation to be successful.

As mentioned above, our manipulation of the embodiment illusion significantly impacted body weight perception and partially impacted the measurements of the feelings of presence and embodiment. Therefore, we decided to explore the potentially mediating effects of presence, VBO, and agency on the relationship between condition and body weight perception. However, the mediator analysis did not show a significant indirect effect of those measurements on body weight perception. Therefore, further exploration of potentially mediating factors is suggested for future work.

2.7.3 Limitations and Future Work

Our work provides interesting new insights into the influences of an embodiment illusion on body weight perception in VR. However, we have also identified some limitations and directions for further research. First, we assume in our work a self-attribution of the virtual body and thus an association of the self with the virtual human triggered by different moderators, such as the feeling of embodiment or avatar personalization. However, no psychometric factors mediating the association have been identified to date. Future research should

(a) systematically test the identified, potentially moderating factors and (b) in addition to our factors, explore potential mediators such as self-identification, emotional connectedness, and perceived similarity.

Second, our study was limited to body weight estimations of a single, non-personalized, virtual human scaled to the participants' body height. However, estimations for a single virtual human strongly depend on its appearance and its model. We used a person of average weight wearing simple clothing without additional accessories. Nevertheless, when using non-personalized avatars, it suggests performing estimations multiple times with uniquely generated or body weight-modified virtual humans. Additionally, the uniform scaling we performed introduced the bias of showing taller participants avatars with higher BMI and vice versa. Future experiments should consider more realistic scaling approaches and body weight self-assessment through modified, personalized avatars.

Third, in our no embodiment illusion condition, participants had no virtual body at all. This led to two inconsistencies between conditions: (a) Participants having no embodiment illusion did not have an egocentric perspective on their body and therefore (b) could not alternately look at their virtual bodies directly and via the mirror. Future work should therefore add another condition, in which participants have a virtual body but still need to estimate the body weight of a other virtual human.

Fourth, we conducted our experiment with a relatively small sample of young and healthy female participants. Future research should consider extended samples, including participants suffering from eating- and body weight disorders within the full range of age groups and also male participants.

2.8 Contribution and Conclusion

To the best of our knowledge, our work is the first to investigate the influence of the embodiment of photorealistic, non-personalized avatars on female body weight perception in VR, considering the impact of the participant's BMI. Contrary to prior work, we used body weight estimations of photorealistic virtual humans with known BMI as an explicit measurement quantifying the differences in body weight perception between conditions and to determine the influence of participant's BMI on the estimations. Using this approach, we could show that an illusion of embodiment highly impacts the perception of non-personalized virtual humans. Our results also indicate that more research is necessary to explore the numerous possible technology-related factors that could affect one's body weight perception when using VR systems, to ensure safe and accurate use in supporting the therapy of body weight misperception, and to further explore body weight perception. The knowledge gained contributes principally to the understanding of our human body weight perception and particularly to the understanding of the perception of virtual humans within VR.

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Copyright

Author Contributions

Erik Wolf conceptualized large parts of the experimental design, developed the Unity application, including the experimental environment and avatar animation system, collected parts of the data, and took the lead in writing the manuscript. Nathalie Merdan supported the conceptualization of the experimental design, adapted the Unity application for the experiment, and collected parts of the data. Nina Döllinger supported the data analysis. David Mal supported the theoretical framing of the work. Mario Botsch provided the avatar reconstruction framework. Carolin Wienrich and Marc Erich Latoschik conceived the original project idea, discussed the study design, and supervised the project. All authors continuously provided constructive feedback and helped to shape the study and the corresponding manuscript.

Chapter 3

Embodiment and Perception of Personalized Avatars in Relation to the Self-Observation Distance in Virtual Reality

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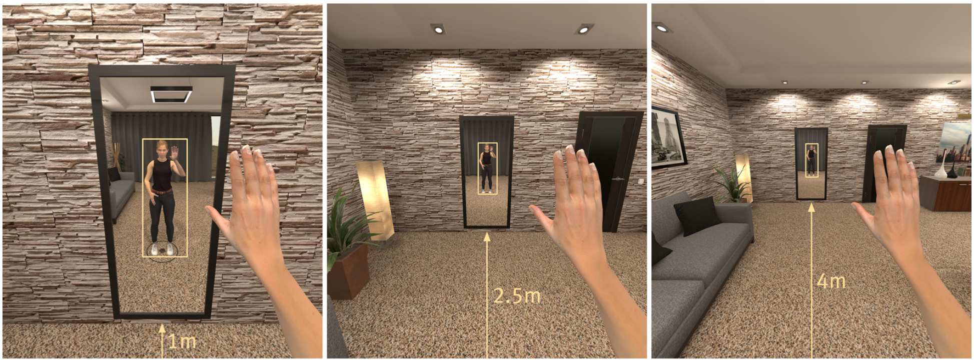

Figure C3.1: The user's first-person perspective monocularly rendered according to the Valve Index HMD rendering parameters for the short (1 m, left), middle (2.5 m, center), and far (4 m, right) self-observation distance. The yellow outlined areas within the virtual mirror highlight the decreasing size of the third-person perspective on the avatar in the user's field of view with increasing self-observation distance.

[1] As part of the dissertation, the published text was editorially revised, with only slight orthographic, stylistic, and formal adjustments, while completely retaining the original semantics.

Abstract

Virtual reality applications employing avatar embodiment typically use virtual mirrors to allow users to perceive their digital selves not only from a first-person but also from a holistic third-person perspective. However, due to distance-related biases such as the distance compression effect or a reduced relative rendering resolution, the self-observation distance (SOD) between the user and the virtual mirror might influence how users perceive their embodied avatar. Our article systematically investigates the effects of a short (1 m), middle (2.5 m), and far (4 m) SOD between users and mirror on the perception of their personalized and self-embodied avatars. The avatars were photorealistic reconstructed using state-of-the-art photogrammetric methods. Thirty participants repeatedly faced their real-time animated self-embodied avatars in each of the three SOD conditions, where they were repeatedly altered in their body weight, and participants rated the (1) sense of embodiment, (2) body weight perception, and (3) affective appraisal towards their avatar. We found that the different SODs are unlikely to influence any of our measures except for the perceived body weight estimation difficulty. Here, the participants perceived the difficulty as significantly higher for the farthest SOD. We further found that the participants' self-esteem significantly impacted their ability to modify their avatar's body weight to their current body weight and that it positively correlated with the perceived attractiveness of the avatar. Additionally, the participants' concerns about their body shape affected how eerie they perceived their avatars. The participants' self-esteem and concerns about their body shape influenced the perceived body weight estimation difficulty. We conclude that the virtual mirror in embodiment scenarios can be freely placed and varied at a distance of one to four meters from the user without expecting major effects on the perception of the avatar.

Keywords

Virtual human, virtual body ownership, agency, body weight perception, body weight modification, affective appraisal, distance compression effect, self-recognition

3.1 Introduction

Avatars are digital self-representations controlled by their users within a virtual environment (Bailenson & Blascovich, 2004). In virtual reality (VR), users can not only control their avatar but also embody it from a first-person perspective, seeing their avatar's virtual body moving where their physical body normally would be located (Debarba et al., 2015; Slater et al., 2010b). In consequence, users can develop the feeling of owning and controlling their virtual body as their own body, called the sense of embodiment (SoE, Kilteni et al., 2012). Unlike the physical body, the virtual body is easily adjustable in various ways (e.g., body shape, body size, skin color). Virtual mirrors are used to make users aware of their altered appearance by providing a holistic third-person perspective on their virtual body (Inoue & Kitazaki, 2021). The observed modified self-appearance can induce human perceptual or behavioral changes based on the Proteus effect (Ratan et al., 2020), which originally describes the phenomenon that users adapt their behavior according to the behavior they expect from the appearance of their embodied avatar (Yee & Bailenson, 2007).

In mental health, the serious application of avatar embodiment can be particularly valuable (Aymerich-Franch, 2020; Matamala-Gomez et al., 2021). A good example is the treatment of body image-related misperceptions of body dimensions (i.e., body weight or size) in body image distortions (World Health Organization, 2019), where the exposition with the own body in a mirror is an elementary part of the treatment strategy (Delinsky & Wilson, 2006; Griffen et al., 2018). To improve such mirror exposure, the embodiment of avatars in VR offers novel opportunities for working on the body perception (Turbyne et al., 2021). Affected individuals may face their photorealistic and highly personalized avatar in a virtual mirror, which can then be realistically modified in its body weight or size (Döllinger et al., 2022c; Mölbert et al., 2018). Hence, scenarios helping to uncover and visualize the individuals' mental body image or to deal intensively with their current or desired body weight are becoming conceivable (Döllinger et al., 2019). A recent review by Turbyne et al. (2021) even showed that the user's mental body image could correspond to the avatar's body after exposure, suggesting great potential for further research and application.

When using embodied avatars as a predefined stimulus for inducing perceptual and behavioral changes in serious applications, it is vital to ensure that users perceive their avatars as intended. However, prior research has shown that system and application-related factors, such as the used display type (Wolf et al., 2020, 2022c), the observation perspective (Neyret et al., 2020a; Thaler et al., 2019), or the application of embodiment itself (Wolf et al., 2021) can inadvertently impact how users perceive their embodied avatar. Another influencing factor could be the self-observation distance (SOD) on the embodied avatar when using a virtual mirror. Imagine a thought experiment in which a mirror moves further and further away from an observer until it reaches a distance at which the observer can no longer recognize the reflection. In the context of virtual mirror exposure, it means that the provided third-person perspective on the predefined stimulus, the embodied avatar, will diminish over distance until the stimulus can not be recognized anymore and its potential effect is gone. Prior work suspects similar (Wolf et al., 2022b, 2022c), as they recently raised the question of whether different SODs might be the reason for observing heterogeneous results between mirror exposure studies. Indeed, although it is known that distance-related biases significantly influence a user's perception of a virtual environment (Kelly, 2022; Renner et al., 2013), no research seems to have yet investigated the effects of the distance between a virtual mirror and the user on the perception of their embodied avatar. Performing a meta-analysis of previous work also seems difficult, as most works using virtual mirrors do not report details about the placement of the virtual mirror in relation to the user's position (e.g., of 17 studies from a review on the Proteus effect, only four reported details on the mirror placement, Ratan et al., 2020). To address the identified research gap, we derive the following research question for our work.

Research Question

> How does the self-observation distance between the user-embodied avatar and its presentation in a virtual mirror affect the user's avatar perception?

To investigate our posed research question, we systematically manipulated the distance between user-embodied avatars and a virtual mirror in a controlled user study. Participants repeatedly observed their embodied avatar at different distances in the virtual mirror and judged it concerning the induced SoE, the perceived body weight, and the affective appraisal. In the following, we present further related work on distance-related factors potentially influencing avatar perception and the different captured measures.

3.2 Related Work

3.2.1 Distance-Related Factors Influencing Avatar Perception

When thinking back to the above-introduced thought experiment and imagining it conducted in VR, some further limitations become apparent. Increasing the distance between an observer and the virtual mirror leads to a decrease of the relative size of the mirror in the presented field of view (FoV) of the observer (Sedgwick, 1986). This ultimately results in a decreased relative size of the mirror compared to the whole rendered scene and, therefore, in a reduced resolution of the avatar. As commercially available HMDs still have a limited display resolution compared to the human eye (Angelov et al., 2020), the resolution of the avatar presented in the virtual mirror decreases much faster when increasing the SOD than it would in reality. Consequently, the observer receives less detailed visual information about the embodied avatar, which might be reflected in an altered perception of the avatar.

Another influencing factor could be the distance compression effect, which states that individuals underestimate egocentric distances (i.e., the distance between an object and its observer) in VR compared to reality (Kelly, 2022; Renner et al., 2013). Although research shows that absolute underestimates are more pronounced above 10 m (Loomis & Knapp, 2003), the effect also occurs at shorter egocentric distances, which are more common in avatar embodiment scenarios (Willemsen & Gooch, 2002). However, the ability to precisely estimate distances is important for creating accurate mental maps of perceived space. These maps are then used to judge the dimensions and positions of objects in space in relation to each other (Epstein et al., 2017; Wienrich et al., 2019). When a distance is misperceived in a virtual environment, the size-distance relations learned in reality are no longer applicable and require cognitive adaptation (Loomis & Knapp, 2003). The reasoning is supported by the size-distance invariance hypothesis, stating that a perceived distance directly relates to an object's perceived size (Gilinsky, 1951; Kelly et al., 2018). A misperceived distance might therefore lead to a subconscious misperception of the size of a presented object like, in our case, an avatar. This would be particularly troubling in the context of the introduced body image-related application (Turbyne et al., 2021). Here, the avatar's dimensions, as a well-defined stimulus, could be misperceived as a consequence of a misjudged distance between the user and the virtual mirror, ultimately compromising the intended perceptual adaption effect. However, as Renner et al. (2013) summarized, there are potential compensational cues improving spatial perception. The most important in the context of our work is the application of avatar embodiment itself, since displaying a virtual body in the first-person perspective can serve as a well-known visual reference partially compensating distance compression effects (Leyrer et al., 2011; Mohler et al., 2010; Ries et al., 2008). Hence, the question arises whether the known spatial distortions lead to a distorted perception of the embodied avatar in the virtual mirror or whether a possible effect is compensated.

To investigate the effects of altered SOD on avatar perception in our study, we manipulated the distance between the avatar-embodied user and the mirror based on the few distances reported in previous studies (Ratan et al., 2020; Turbyne et al., 2021). We ensured that our tested range covered the extracted distances (i.e.,1 m to 2.5 m), and extended the range further to four meters for covering potentially larger distances not reflected in prior work. Due to the drastically reduced relative size of the avatar reflection in the virtual mirror, we considered distances greater than four meters irrelevant for practical use in mirror exposure. To check whether participants recognized the manipulation of the SOD and whether a distance compression effect occurred, we formulate the following hypotheses.

Hypotheses

H1.1: A variation of the SOD has a significant influence on the estimation of the perceived egocentric distance to the virtual mirror.

H1.2: The perceived egocentric distance to the virtual mirror will be underestimated compared to the actual SOD.

3.2.2 Assessing Avatar Perception

Various measures are suitable to capture the effects of SOD variations on avatar perception. In the following, we present measures that we consider relevant in the context of mirror exposure for behavioral and perceptual adaption. We further classify the expected effects of an altered SOD on the measures in relation to the potentially influencing factors described above.

Sense of Embodiment, Self-Similarity, and Self-Attribution

A user's subjective reaction to embodying an avatar can be captured by the aforementioned SoE, which is also considered a strong moderator of activating behavioral and perceptual adaptation in mirror exposure (Kilteni et al., 2013; Mal et al., 2023). The SoE originates from coherence between corresponding body-related sensory impressions perceived simultaneously in reality and virtuality, leading to the feeling of really owning and controlling the avatar's virtual body (IJsselsteijn et al., 2006; Slater et al., 2009, 2010b). It comprises three components: (1) Virtual body ownership (VBO) is the feeling of really owning the virtual body, (2) agency is the feeling of controlling the virtual body, and (3) self-location is the feeling of being in the virtual body (Kilteni et al., 2012). For assessing the sub-components, well-established standardized questionnaires can be used (Peck & Gonzalez-Franco, 2021; D. Roth & Latoschik, 2020).

When investigating the influence of SOD on avatar perception in mirror exposure scenarios, it plays an important role on which observation perspective an impression is based (e.g., first-person, third-person, or a combination of both). We expect that only when the third-person perspective is crucial for assessing an impression, an altered SOD to the mirror can influence the results of the corresponding measure. For example, the feeling of VBO is expected to rise when a user receives a third-person perspective on the embodied avatar, as the holistic view of the body, including the face, provides more potential cues for self-recognition (Inoue & Kitazaki, 2021; Spanlang et al., 2014). However, the cues might be less recognizable when the mirror image is rendered on a lower resolution in the FoV due to an increased SOD. This is particularly relevant in the case of personalized avatars since areas of the face are considered to be important for self-recognition (Tsakiris, 2008). Waltemate et al. (2018) further showed that avatar personalization significantly increases VBO. Hence, when important cues for self-recognition (e.g., self-similarity and self-attribution, Fiedler et al., 2023a) are no longer recognizable at an increased SOD, a reduced feeling of VBO can be expected. Furthermore, a potential distance compression effect could impact VBO by potentially breaking the plausibility of the body representation (Latoschik & Wienrich, 2022), as the perceived size of the avatar in the mirror might not match the user's expectations acquired from the real world.

On the contrary, the feeling of agency refers to controlling the avatar's movements that are perceivable in both third-person and first-person perspectives. Here, we expect a potential distance compression effect to have no impact on agency (Gonzalez-Franco et al., 2019). Although the distance to the third-person representation could be subjectively misjudged, the movements are still clearly visible in the first-person perspective. Moreover, Gorisse et al. (2017) showed that the sense of agency is similarly pronounced when receiving visuomotor feedback from first-person and third-person perspectives. It suggests that the first-person perspective is generally sufficient to evoke a sense of agency. Consequently, a reduced resolution in the simultaneously presented third-person perspective should have a negligible effect on agency. Similarly, Debarba et al. (2017) showed that agency is insensitive to a change in the observation perspective as long as there are no multisensory inconsistencies in the embodiment. Hence, we do not expect an altered SOD to influence the sense of agency as long as a first-person perspective is simultaneously presented.

Similarly, the feeling of self-location seems to be mainly driven by having a first-person perspective on the avatar's virtual body. It might only be affected by the third-person perspective when a strong incongruence between spatial localization in both perspectives occurs (Gorisse et al., 2017; Kilteni et al., 2012). An example could be a curved or distorted mirror which breaks the plausibility of the mirror reflection by showing the avatar in a different location as the user would expect it, thus questioning the fact that the user is really embodying the avatar (Higashiyama & Shimono, 2004; Inoue & Kitazaki, 2021). We expect that a potential distance compression effect would not lead to such an incongruence between the provided perspectives. Moreover, we do not expect a reduced resolution of the mirror image to affect self-location, as it rather removes than distorts the third-person perspective. Hence, we expect that modifying only the SOD on the third-person perspective will not significantly impact self-location in usual embodiment scenarios. Based on the reasoning regarding the influence of SOD on the different dimensions of SoE, self-similarity, and self-attribution presented in this section, we hypothesize the following.

Hypotheses

H2.1: An increase in the SOD results in a lower VBO, self-similarity, and self-attribution towards the embodied avatar.

H2.2: A variation of the SOD does not affect agency and self-location towards the embodied avatar.

Body Weight Estimation

In the proposed serious application of avatar embodiment in virtual mirror exposure for treating body image-related misperceptions, the estimation of body weight can be a valuable tool for investigating and working on a user's body image (Döllinger et al., 2022c; Thaler, 2019). However, when using the avatar as a body image-related stimulus, care should be taken to ensure that the avatar's virtual body is perceived accurately without being distorted by individual-, system- or application-related factors. To explore such factors, prior works modified the body weight of static photorealistic virtual humans and used body weight estimations to discover influences of the avatar personalization or the estimators' gender or body weight (Mölbert et al., 2018; Piryankova et al., 2014a; Thaler et al., 2018a, 2018b). Wolf et al. (2020, 2022b, 2022c) further highlighted vast differences in avatar perception between different kinds of VR and augmented reality (AR) displays using a similar approach but with embodied avatars.

Concerning the role of the SOD on body weight perception, Thaler et al. (2019) showed significant differences in body weight estimations between first- and third perspectives, highlighting the third-person perspective as more accurate and important. Neyret et al. (2020a) further compared the influence of perspective on general avatar perception and highlighted the importance of a third-person presentation for providing a less self-biased view of the avatar. As the impression of an embodied avatar's body weight seems to be driven by the third-person perspective, our introduced distance-related factors potentially impact the perception of the avatar's body weight. However, it is likely that the learned proportions of a familiar body obscure any potential effects that could be attributed to a misperception of egocentric distances (Gonzalez-Franco et al., 2019; Mohler et al., 2010; Renner et al., 2013). Especially when using personalized avatars, we consider body-related cues as particularly strong as we usually know exactly the proportion between, for example, our arm's length and other body dimensions (Stefanucci & Geuss, 2009). This has also been noticed by Higashiyama and Shimono (2004), who already suspected a person's familiarity as a potential reason for violations of the size-distance invariance hypothesis when estimating a person's size at different distances. However, empirical evidence in the context of our work is still pending. Another open question is at what SOD the resolution of the displayed avatar is reduced to such an extent that body weight can no longer be reliably estimated and whether this distance is within the relevant range for practical application. Although it can be deductively inferred that an avatar's body weight will be more difficult and uncertain to estimate, no work seems to have addressed this issue before. Based on the reasoning regarding the influence of SOD on body weight perception presented in this section, we hypothesize the following.

Hypotheses

- H3.1: A variation of the SOD does not affect the overall estimations of the embodied avatar's body weight.
- H3.2: An increase in the SOD results in a higher uncertainty in estimating the embodied avatar's body weight.
- H3.3: An increase in the SOD results in a higher perceived difficulty in estimating the embodied avatar's body weight.

Affective Appraisal

When working on body perception in VR, different work suggests using photorealistically personalized avatars (Döllinger et al., 2022c; Mölbert et al., 2018; Turbyne et al., 2021). However, highly realistic human-like avatars are prone to fall into the Uncanny Valley (Mori, 1970), which could affect the plausibility and credibility of the whole experience (Latoschik & Wienrich, 2022) and possibly prevent behavioral and perceptual adaptation effects (Wienrich et al., 2021a). In general, the Uncanny Valley defines a perceptual range in which the affective appraisal of an avatar paradoxically changes from pleasant to uncanny as soon as it approaches but has not yet fully reached a human-like representation (Mori et al., 2012). To measure the affective appraisal of an avatar regarding the Uncanny Valley effect, Ho and MacDorman (2017) introduced a revised version of their questionnaire, often denoted as the "Uncanny Valley Index", for capturing the perceived humanness, attractiveness, and eeriness of an avatar.

There has been prior work on the affective appraisal of virtual humans in dependence on different factors like their stylistics (Hepperle et al., 2020, 2022), reconstruction method (Bartl et al., 2021b), anthropomorphism (Chaminade et al., 2007; Lugrin et al., 2015), or the display type they are perceived with (Hepperle et al., 2022; Wolf et al., 2022c). However, no work seems to explore the effects of altering SOD. In the context of our study, we assume that the avatar's relative size in the user's FoV, and hence its rendering resolution, impact the avatar's affective appraisal. Especially when using photorealistically personalized avatars with an almost reality-like appearance, as in our and similar works, users may be more attentive to their avatar's appearance. For example, Döllinger et al. (2022c) noticed in their qualitative evaluation that minor defects in the reconstruction of personalized avatars might lead to a strong feeling of uncanniness, especially in the facial area. This is in line with Bartl et al. (2021b), who asked participants to increase the distance between themselves and two differently reconstructed avatars until they could no longer tell which reconstruction was superior. Interestingly, participants chose a larger distance for personalized avatars than for generic avatars, indicating that small reconstruction errors are more significant on personalized avatars. As a presented avatar's resolution decreases with increasing SOD, the resulting blurred avatar rendering potentially hides reconstruction inaccuracies and self-recognition cues (similar to VBO). While we assume that the avatar will always similarly be recognizable as a human-like being, we expect that an altered SOD will impact eeriness and attractiveness. Based on the reasoning regarding the influence of SOD on affective appraisal presented in this section, we hypothesize the following.

Hypotheses

H4.1: A variation of the SOD does not affect the perceived humanness of the embodied avatar.

H4.2: An increase in the SOD results in a lower perceived eeriness and a higher perceived attractiveness of the embodied avatar.

3.3 Materials and Methods

In our user study, we systematically manipulated the distance between the embodied avatar and virtual mirror between a short (1 m), medium (2.5 m), and far (4 m) distance. A total of 30 participants repeatedly embodied a photorealistically personalized avatar using a state-of-the-art consumer VR setup, including body tracking. During the VR exposure, participants performed various body movement and body weight estimation tasks in front of a virtual mirror. The body weight estimation consisted of an active modification task (AMT) and a passive estimation task (PET). In the AMT, participants had to modify their avatar's body weight actively to their current, ideal, and the population's average body weight. In the PET, the system repeatedly modified the avatar's body weight while participants had to estimate it. After exposure, participants answered questions regarding their SoE and affective appraisal of the avatar. Before conducting the study, we obtained ethical approval from the ethics committee of the Institute Human-Computer-Media (MCM) of the University of Würzburg without further obligations.

Concerning our manipulation, we expected that the variation of the SOD would be reflected in participants' distance estimations (H1.1) and that there would be a distance compression effect across all SODs (H1.2). For our results, we expected that an increased SOD would cause a declined feeling of VBO, self-identification, and self-attribution (H2.1), while there would be no differences in agency and self-location (H2.2). We further predicted that there would be no differences in the estimation of the avatars' body weight (H3.1) but that the body weight estimation difficulty and uncertainty would rise with increasing SOD (H3.2 and H3.3). Lastly, we assumed that the participants would not perceive any differences in the avatar's humanness (H4.1) but that eeriness of the avatar would decrease and that the attractiveness would rise with increasing SOD (H4.2). In summary, our study systematically investigates the influence of the distance between the avatar and the virtual mirror in mirror exposure scenarios by capturing the user's perception and appraisal of the embodied avatar for the first time. It thus contributes to uncovering unintended influences that could arise from an uncontrolled SOD.

3.3.1 Participants

The study took place in a quiet laboratory at the University of Würzburg. We recruited a total of 30 bachelor students (19 female, 11 male) who received course credit in return. Prior to the experiment, we determined the following inclusion criteria: Participants should (1) dress appropriately for the body scan according to previously given instructions (e.g., tight clothes, no jewelry, hair tied together), (2) have a normal or corrected-to-normal vision, (3) have no known sensitivity to motion and simulator sickness, and (4) not have been suffering from any mental or psychosomatic disease or body weight disorders. No participants had to be excluded. All participants were German native speakers. Six participants had no VR experience, 16 had used it between two and ten times before the experiment, five between 11 and 20 times, and three had used it more than 20 times. Therefore, most participants can be considered rather inexperienced with VR. Further demographic information and descriptive values for the sample-related control measures (explained in Section 3.3.3) can be found in Table C3.1.

Measure	Range	M (SD)
Demographics		
Age	18 – 25	21.66 (1.58)
Body height (m)	1.56 – 1.90	1.70 (0.09)
Body weight (kg)	45.10 – 110	67.73 (14.94)
BMI	17.44 – 35.11	23.37 (3.93)
Controls		
Pre-SSQ	0 – 74.80	13.34 (15.70)
Post-SSQ	0 – 89.76	16.34 (22.34)
RSES	9 – 29	20.93 (4.76)
BSQ	34 – 138.13	79.62 (26.36)

Table C3.1: Age, body measurements, and the scores of the control variables of our sample.

3.3.2 Design

In a counterbalanced within-subjects design, the independent variable was the *self-observation distance (SOD)*, i.e., the distance between the avatar and mirror, with three different levels: short (1 m), middle (2.5 m), and far (4 m). As dependent variables, we captured (1) *SoE*, (2) *body weight perception*, and (3) *affective appraisal*. SoE consists of the feeling of *VBO*, *agency*, and *self-location*. Additionally, we extended the SoE exploratively by the self-recognition-related feelings of *self-similarity* and *self-attribution*. Body weight perception consists of *body weight estimations* performed in the *AMT* and *PET* and the respective *estimation difficulty*. The affective appraisal consists of *humanness*, *eeriness*, and *attractiveness*. We further controlled for the participant's (1) *self-esteem*, (2) *body shape concerns*, and (3) *perceived distance to the mirror*. All measures are explained in detail below.

3.3.3 Measures

Participants gave their answers on our measures either verbally during the VR experience or on a separate PC using LimeSurvey 4 (LimeSurvey GmbH, 2020) before and after the VR exposure. The exact measurement time for each measure can be found in Section 3.3.6. To conduct the questionnaires with German participants, we either used existing validated German versions of the questionnaires or translated the items to the best of our knowledge using back-and-forth translation.

Sense of Embodiment, Self-Similarity, and Self-Attribution

The feeling of VBO and agency was measured using the Virtual Embodiment Questionnaire (VEQ, D. Roth & Latoschik, 2020). Participants answered four items for each dimension on a scale from 1 to 7 (*7 = highest VBO, agency*). To capture the participants' feelings of self-location, self-similarity, and self-attribution towards their avatars, we exploratively extended the VEQ by four items for each of the added dimensions. The items were either created by ourselves or adapted from different prior work and rephrased to match the usual VEQ item phrasing. We call these new items VEQ+ in the course of our work. Following the VEQ, the items were captured on a scale from 1 to 7 (*7 = highest self-location, self-similarity, self-attribution*) and presented with the same instructions. The following list contains the items for each dimension, including the source when not self-created.

Self-Location

1. I felt as I was located within the virtual body (Gonzalez-Franco & Peck, 2018).
2. I felt like I was located out of my body (Gonzalez-Franco & Peck, 2018).
3. I felt like my body was drifting towards the virtual body (Gonzalez-Franco & Peck, 2018).
4. I felt like my body was located where I saw the virtual body (Debarba et al., 2015).

Self-Similarity

1. The appearance of the virtual human's face was similar to my face (Thaler et al., 2019).
2. The overall appearance of the virtual person was similar to me (Thaler et al., 2019).
3. I felt like the virtual human resembled me.
4. The appearance of the virtual human reminded me of myself.

Self-Attribution

1. I felt like the virtual human was me (Romano et al., 2014).
2. I could identify myself with the virtual human.
3. I had the feeling that the virtual human was behaving the way I would behave.
4. I felt like the virtual human had the same attributes as I have.

Body Weight Perception

In our study, body weight perception comprises the two measurements explained below. The first captures the body weight estimations of the embodied avatar, while the second one captures the difficulty of the estimations. All measurements were taken during the VR exposure.

Body Weight Estimation We captured the participant's body weight estimations in kg during the AMT and PET as explained in Section 3.3.5. For estimations of the current body weight, we calculated the misestimation M based on the modified body weight m and the participant's real body weight r as $M = \frac{r-m}{r}$. For the participant's estimations from the PET, we calculated the misestimation M for each performed body weight modification as $M = \frac{e-p}{p}$, where e is the estimated body weight, and p is the presented body weight of the avatar. A negative value of M always constitutes an underestimation of the avatar's body weight, and a positive value constitutes an overestimation. Additionally, we calculated for all estimations (1) the average misestimation $\overline{M} = \frac{1}{n}\sum_{k=1}^{n} M_k$ and (2) the absolute average percentage of misestimation as $\overline{A} = \frac{1}{n}\sum_{k=1}^{n} |M_k|$. Since $\overline{M}$ considers under- and overestimations that may cancel each other out between different trials and participants, the results demonstrate the general ability to estimate the absolute body weight of the avatar across multiple trials. Therefore, it can be used to highlight systematic biases in the avatar perception between conditions. Since $\overline{A}$ accumulates only the absolute amount of misestimations and does not take its direction into account, it operationalizes the magnitude of individual estimates. Therefore, it can be used as a good indicator of the difficulty of estimations between conditions. The higher the value, the more difficult the estimate. We refer to Döllinger et al. (2022c) and Wolf et al. (2022c) for advanced analysis of the proposed measures.

Body Weight Estimation Difficulty We measured the participants' perceived difficulty in estimating the avatars' body weight during the PET. For this reason, we used a single-item scale ranging from 0 to 220 (220 = highest difficulty). The scale was inspired by the work of Eilers et al. (1986), a German version of the Rating Scale Mental Effort (Arnold, 1999; Zijlstra, 1993), and rephrased to capture difficulty instead of effort. Its range is defined by non-linearly plotted text anchors serving as estimation reference points enhancing the psychometric properties of the captured data.

Affective Appraisal

We measured the participants' affective appraisal of their avatars using the revised version of the Uncanny Valley Index (UVI, Ho & MacDorman, 2017). It includes three sub-dimensions: *humanness*, *eeriness*, and *attractiveness*. Each dimension is captured by four or five items ranging from 1 to 7 (*7 = highest humanness, eeriness, attractiveness*).

Controls

Distance Estimation To control whether a distortion in distance perception occurred already at our relatively small distances between the avatar and mirror, we asked the participants to estimate the distance between them and the virtual mirror in meters. As found by Philbeck and Loomis (1997), the verbal estimation of distance serves as a reliable measure of the perceived distance. The distance misestimation M is calculated as $M = e - t$, where e is the estimated distance and t is the true distance.

Self-Esteem Since low self-esteem is considered to be linked to a disturbed body image (O'Dea, 2012), we captured the participants' self-esteem as a potential factor explaining deviations in body weight perception. For this purpose, we used the well-established Rosenberg Self-Esteem Scale (RSES, Ferring & Filipp, 1996; Rosenberg, 2015; M. Roth et al., 2008). The score of the questionnaire ranges from 0 to 30. Scores below 15 indicate low self-esteem, scores between 15 and 25 can be considered normal, and scores above 25 indicate high self-esteem.

Body Shape Concerns To control for the participant's body shape concern as a potential confounding factor of our body weight perceptions measurements (Kamaria et al., 2016), we measured participants' tendencies for body shape concerns using the validated shortened form of the Body Shape Questionnaire (BSQ, Cooper et al., 1987; Evans & Dolan, 1993; Pook et al., 2002). The score is captured with 16 different items and ranges from 0 to 204 (*204 = highest body shape concerns*).

Simulator Sickness To control for possible influences of simulator sickness caused by latency jitter or other sources (Stauffert et al., 2018, 2020), we captured the presence and intensity of 16 different typical symptoms associated with simulator sickness on 4-point Likert scales using the Simulator Sickness Questionnaire (SSQ, Bimberg et al., 2020; Kennedy et al., 1993). The total score of the questionnaire ranges from 0 to 235.62 (*235.62 = strongest simulator sickness*). An increase in the score by 20 between a pre- and post-measurement indicates the occurrence of simulator sickness (Stanney et al., 1997).

3.3.4 Apparatus

The technical system used in our study closely followed the technical system developed and evaluated in previous work by Döllinger et al. (2022c). A video showing the system is provided in the supplementary material of this work. All relevant technical components will be explained in the following.

Soft- and Hardware

To create and operate our interactive, real-time 3D VR environment, we used the game engine *Unity* 2019.4.20f1 LTS (Unity Technologies, 2019). Our hardware configuration consisted of a *Valve Index* VR HMD (Valve, 2020c), two handheld *Valve Index Controllers*, one *HTC Vive Tracker 3.0* positioned on a belt at the lower spine, and one further tracker on each foot fixed by a velcro strap. The hardware components were rapidly (22 ms) and accurately (within a sub-millimeter range) tracked by four *SteamVR Base Stations 2.0* (Niehorster et al., 2017). According to the manufacturer, the HMD provides a resolution of 1440×1600 px per eye with a total horizontal field of view of $130°$ running at a refresh rate of 90 Hz. However, the perspective calculated using the perspective projection parameters of the HMD, which can be retrieved from the *OpenVR* API using an open-source tool [2], results in a maximum monocular FoV of $103.6 \times 109.4°$ and an overlap in the stereo rendering of $93.1°$, providing a total FoV of $114.1 \times 109.4°$. Thus, the actual pixel density in the FoV was 13.9×14.6 PPD. Figure C3.1 shows the user's FoV for our three conditions. All VR hardware was integrated using *SteamVR* (Valve, 2021) in version 1.16.10 and the corresponding Unity plugin in version 2.7.3 [3]. The whole system ran on a high-end VR PC composed of an *Intel Core i7-9700K*, an *Nvidia RTX2080 Super*, and *32 GB RAM* running *Windows 10*.

To ensure participants received a sufficient frame rate and to preclude a possible cause of simulator sickness, we measured motion-to-photon latency by frame-counting (He et al., 2000; Stauffert et al., 2020, 2021). To perform the measurement, we split the video output of our VR PC into two signals using an *Aten VanCryst VS192* display port splitter. One signal still led to the HMD, the other to an *ASUS ROG SWIFT PG43UQ* low-latency gaming monitor. A high-speed camera of an *iPhone 8* recorded the user's motions and the corresponding

[2] https://github.com/PeterTh/ovr_rawprojection

[3] https://assetstore.unity.com/packages/tools/integration/steamvr-plugin-32647

reactions on the monitor screen at 240 fps. By analyzing 20 different movements each, the motion-to-photon latency was determined to be 14.4 ms ($SD = 2.8$ ms) for the HMD and 40.9 ms ($SD = 5.4$ ms) for the further tracked hardware devices. Both measurements were considered sufficiently low to provide a fluent VR experience and a high feeling of agency towards the avatar (Waltemate et al., 2016).

Virtual Environment

The virtual environment used in our study was based on an asset obtained from the Unity Asset Store [4] that we modified for our purposes. To create a suitable area for self-observation at different SODs, we removed some of the original objects and added a custom-written virtual mirror based on a planar reflection shader to the wall. Figure C3.1 shows the different SODs within the environment from the user's first-person perspective. When changing the SODs, the real-time lighting of the room was also shifted to keep lighting and shadow casting consistent across conditions. We further added a curtain in front of the room's window to limit the visual depth in the mirror background. Depending on the current condition and SOD, a marker on the floor of the virtual environment indicated where participants had to stand during the exposure. Automatic realignment of the environment ensured that participants did not have to change their position in the real world. To this end, we used a customized implementation of the *Kabsch algorithm* [5] (Müller et al., 2016), which uses the positions of the SteamVR base stations as physical references. Additionally, the virtual ground height was calibrated by briefly placing the controllers onto the physical ground.

Avatar Generation

We created the participants' personalized avatars using a photogrammetry rig and the method for avatar generation described by Achenbach et al. (2017). The rig consists of 106 *Canon EOS 1300D DSLR cameras* arranged in circles around the participant (see for a detailed description Bartl et al., 2021b). The cameras trigger simultaneously, creating a holistic recording of the person in a series of individual images. This set of images is then fed into the avatar generation pipeline of Achenbach et al. (2017), which creates an animatable, personalized avatar from the individual images in less than 10 min. The pipeline uses *Agisoft Metashape* (Agisoft, 2021) for photogrammetric reconstruction to process the set of images into a dense point cloud. It then fits a template model to the point cloud and calculates the avatar's texture. The template model is fully rigged so that the resulting avatar is ready for

[4]https://assetstore.unity.com/packages/3d/props/interior/manager-office-interior-107709
[5]https://github.com/zalo/MathUtilities/#kabsch

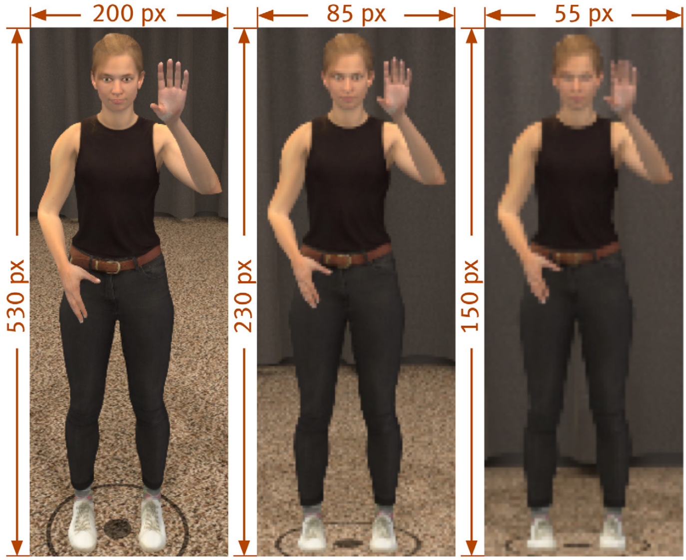

Figure C3.2: Enlargements of the yellow outlined areas in Figure C3.1 following the same order. They illustrate the effects of reducing the relative size of the avatar in the user's entire field of view by increasing the SOD. The resulting resolutions are plotted next to the images.

use in embodied VR without manual post-processing. Figure C3.2 shows an avatar generated by the described method in the different distance-depended resolutions of our experiment. In our experiment, the avatar generation pipeline ran on a PC containing an *Intel Core i9-9900KF*, an *Nvidia RTX2080 Ti*, and *32 GB RAM* running *Ubuntu 20*.

To enable quick integration of the avatars during the experiment, we used a custom-written FBX-based importer to load the avatars during runtime into our Unity application. The importer is realized through a native Unity plugin which automatically generates a fully rigged, humanoid avatar object which is immediately ready for animation. This approach avoids error-prone manual configuration for each user, as it would be required when using Unity's built-in FBX import system.

Avatar Animation

We animated the generated avatars during the study in real-time according to the user's body movements. Since recent investigations indicate that VR equipment-based full-body tracking solutions combined with *Inverse Kinematics* (IK, Aristidou et al., 2018) can achieve similar results in motion tracking quality (Spitzley & Karduna, 2019; Vox et al., 2021) and embodiment-related measurements (Wolf et al., 2020, 2022b) as professional full-body track-

Figure C3.3: Visualization of the body weight modification in a BMI range from 16 to 32 in two-point increments using an exemplary reconstructed avatar of a female person with an original BMI = 19.8. The image is taken from Döllinger et al. (2022c)

ing solutions, we decided to use no dedicated motion tracking system in our work. Therefore, the participants' movements were continuously captured using the introduced HMD, controllers, and trackers. After a short user calibration in T-Pose using a custom-written calibration script, the received poses of the tracking devices were combined with the Unity plugin *FinalIK* version 2.0 [6] to continuously calculate the user's body pose. The calculated body pose was retargeted to the imported personalized avatar in the next step. To avoid potentially occurring inaccuracies in the alignment of the pose or the end-effectors (e.g., sliding feet, end-effector mismatch), we applied a post-retargeting IK-supported custom pose optimization step to increase the avatar animation quality after retargeting.

Avatar Body Weight Modification

To dynamically alter the generated avatars' body weight, we use the method described by Döllinger et al. (2022c). They build a statistical model of human body shapes by performing a Principal Component Analysis on a set of registered meshes, which are generated by fitting a template mesh to scans from the European subset of the CAESAR database (Robinette et al., 2002). A mapping between the parameters of the shape space and the anthropometric measurements provided by the CAESAR database is learned through linear regression (Allen et al., 2003). This provides a way to map the desired change in body weight to a change in body shape at an interactive rate during runtime. Figure C3.3 shows an example of the method's

[6] https://assetstore.unity.com/packages/tools/animation/final-ik-14290

Figure C3.4: Sketch of the body weight modification interaction through gestures. Participants had to press the trigger buttons on each controller and move the controllers either apart (increase body weight) or together (decrease body weight).

results. The body weight modification is integrated into Unity using a native plugin that receives the initial vertex positions of the avatar and applies the above-described statistical model of weight gain/loss.

When performing the AMT in VR, users could modify their avatar's body weight by altering the body shape using gesture interaction, as introduced by Döllinger et al. (2022c). To modify the avatar's body weight, users had to press each trigger button of the two controllers while either moving the controllers away from each other or together (see Figure C3.4). When moving the controller, the body weight changed according to the relative distance change between the controllers r in m/s, following the equation $v = 3.5r^2 + 15r$, where v is the resulting body weight change velocity in kg/s. Moving the controllers away from each other increased the body weight, while moving them together decreased it. The faster the controllers were moved, the faster the body weight changed. As suggested by Döllinger et al. (2022c), body weight modification was restricted to a range of ± 35 % of the user's body weight to avoid unrealistic or uncomfortable body shape deformation.

3.3.5 Experimental Tasks

We chose the following experimental tasks to induce SoE in participants and to encourage them to focus their attention on their avatar to capture the participant's avatar perception as accurately and controlled as possible.

Body Movement Task

Participants had to perform five body movements (i.e., waving with each arm, walking in place, circling arms, circling hip) in front of a virtual mirror to accomplish synchronous visuomotor stimulation suggested by Slater et al. (2010b) and to get the feeling that they were really embodying their avatar. They were asked to observe the body movements of their avatar alternately in the first- and third-person perspective. The movement tasks have been adopted from Wolf et al. (2020).

Active Modification Task (AMT)

Participants had to modify their avatar's body weight by interactively altering its body shape multiple times. We followed Thaler (2019) and Neyret et al. (2020a) and asked participants to modify their avatar's body weight to (1) their current, (2) their desired body weight, and (3) the guessed average body weight in the population (as they defined it). Before each task, the avatar's body weight was set to a random value between ± 5 % and ± 10 % of the original body weight of the avatar. To avoid providing any hints on the modification direction, the HMD was blacked-out during that pre-modification. For modifying the body weight, participants used gesture interaction, as explained in Section 3.3.4. The AMT had to be performed twice per condition to compensate for possible outliers in a single estimation (see Figure C3.5).

Passive Estimation Task (PET)

The PET followed prior work (Wolf et al., 2020, 2021, 2022b, 2022c) and was used to measure the participants' ability to estimate the repeatedly modified body weight of their avatar numerically in kg. The original body weight of the avatar was modified within a range of ± 20 % in ± 5 % increments in a counterbalanced manner, resulting in $n = 9$ modifications, including the original body weight. As in the AMT, the HMD was blacked-out during the modification to avoid any hints. In both AMT and PET, participants were asked to move and turn in front of the virtual mirror to provide a holistic picture of their avatar, as suggested by prior work (P. L. Cornelissen et al., 2018; Döllinger et al., 2022c; Thaler et al., 2019).

3.3.6 Procedure

The experimental procedure was divided into three major phases depicted in Figure C3.5. In the opening phase, the experimenter first welcomed the participants and provided information about the current COVID-19 regulations, which they had to comply with and sign for. Afterwards, they received information about the body scan and experiment, generated pseudonymization codes for avatar and experimental data, gave consent for participation, and had the opportunity to ask questions about the whole procedure.

The body scan phase followed, in which the participants first received instruction on the precise procedure for the body scan (e.g., no jewelry and shoes, required pose). Subsequently, the body height and weight of the participants were recorded, and two body scans of the per-

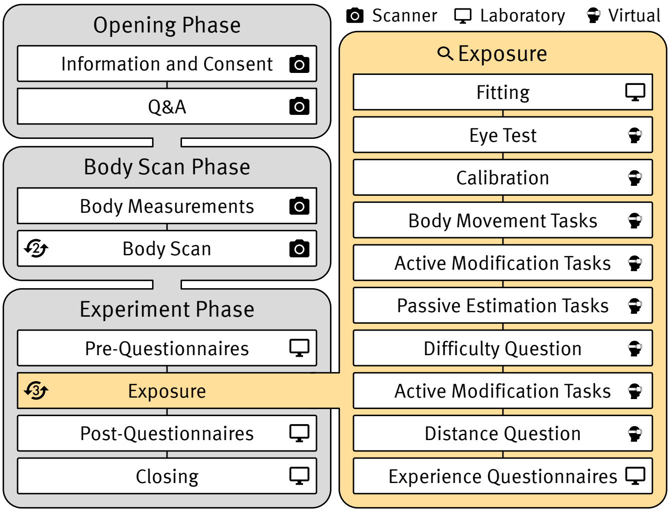

Figure C3.5: Overview of the experimental procedure (left) and a detailed overview of the repeated part of the exposure phase (right). The icons on the right side of each step show in which environment the step was conducted. The icons on the left side indicate the repetition of steps.

son were taken. After a brief visual inspection of the taken images, the avatar reconstruction pipeline was started, and the participants were guided to the laboratory where the actual experiment took place.

In the experiment phase, participants first answered the pre-questionnaires (demographics, RSES, BSQ, and SSQ) and got a quick introduction to the VR equipment. Three VR exposures followed that proceeded for each of our conditions as follows. First, the participants put on the VR equipment while the experimenter ensured they wore it correctly. After the fitting, a pre-programmed experimental procedure started, and participants entered the preparation environment. All instructions were displayed on an instruction panel in the virtual environment and played as pre-recorded voice instructions. The display was blackened for a short moment for all virtual transitions during the VR exposure. Immediately after entering the virtual environment, participants performed a short eye test to validate the HMD settings and confirm appropriate vision. The embodiment calibration followed, and participants could shortly practice modifying their avatars' body weight through gestures before the experimental tasks started (see Section 3.3.5). After the experimental tasks, the control question regarding the perceived distance to the mirror followed before participants left VR to answer the VEQ, VEQ+, and UVI. The distance to the mirror changed for each exposition in a counterbalanced manner. After the final exposition run, participants filled in the post-SSQ. The duration of one VR exposure averaged 12.35 min. The whole experimental procedure averaged 93 min.

3.4 RESULTS

We used *SPSS* version 27.0.0.0 (IBM, 2020) to analyze our results statistically. Before running the statistical tests, we checked whether all variables met the assumption of normality and sphericity for parametric testing. For variables meeting the requirements, we performed a repeated-measures ANOVA (i.e., self-location, self-attribution, AMT current $\overline{M}$, PET $\overline{M}$, humanness, eeriness, attractiveness). Otherwise, we performed a Friedman test(i.e., VBO, agency, self-similarity, AMT current $\overline{A}$, AMT ideal, AMT average, PET $\overline{A}$, PET estimation difficulty, distance estimation, distance misestimation). We calculated all tests against an α of .05. Table C3.2 summarizes the descriptive values of all variables we compared between our conditions. Additionally, we performed a sensitivity analysis using *G*Power* version 3.1.9.7 (Faul et al., 2009). To strengthen the results of non-significant differences, we performed a sensitivity analysis with a group size of $n = 30$, a pre-specified α-level of .05, and a power of .80. Results showed that a Friedman test would have revealed effects of Kendall's $W = 0.1$ or greater. A repeated-measures ANOVA would have revealed effects of Cohen's $f = 0.238$ or greater (Cohen, 2013). Hence, differences with smaller effect sizes could have remained undetected. To exclude sequence effects due to our within-subject design, we also performed our statistical analysis comparing only the first condition completed by each participant in a between-subject design. Apart from minor descriptive differences, the results did not differ from the presented results. Since self-esteem (RSES) and body shape concerns (BSQ) were captured on an individual basis and not per condition (see Table C3.1 for descriptive results), we calculated Pearson correlations between both variables and each dependent variable for control purposes. In case of a significant correlation, we further calculated a simple linear regression to determine the predicting effect of the control variable. The test results are reported in the corresponding sections below.

3.4.1 DISTANCE ESTIMATION

We controlled for successfully manipulating our conditions and assumed that participants would estimate the distance to the virtual mirror by increasing the SOD significantly higher. We found significant differences in the distance estimations between our SODs, $\chi^2(2) = 59.51, p < .001, W = 0.992$. Two-tailed Wilcoxon signed-rank post-hoc tests revealed a

Measure	Range	Short M (SD)	Middle M (SD)	Far M (SD)
Sense of Embodiment (SoE)				
VEQ VBO	[1 – 7]	5.07 (1.06)	5.05 (1.07)	5.18 (1.15)
VEQ Agency	[1 – 7]	6.17 (0.71)	6.00 (0.78)	6.18 (0.67)
VEQ+ Self-Location	[1 – 7]	4.41 (0.93)	4.43 (0.93)	4.48 (0.96)
VEQ+ Self-Similarity	[1 – 7]	5.48 (0.88)	5.41 (0.87)	5.63 (0.98)
VEQ+ Self-Attribution	[1 – 7]	4.93 (1.25)	4.99 (1.13)	5.05 (1.31)
Body Weight Perception				
AMT Cur. Misestimation ($\overline{M}$)		-0.62 (4.14)	0.11 (4.62)	-0.93 (4.67)
AMT Cur. Abs. Misestim. ($\overline{A}$)		3.86 (2.40)	4.26 (2.89)	4.26 (2.88)
AMT Ideal BMI		22.21 (3.29)	21.91 (3.12)	21.73 (2.81)
AMT Average BMI		25.17 (3.00)	25.70 (3.04)	25.31 (3.16)
PET Misestimation ($\overline{M}$)		-0.06 (6.69)	-0.23 (6.72)	-0.36 (7.46)
PET Abs. Misestimation ($\overline{A}$)		6.86 (3.81)	7.59 (3.21)	7.44 (3.33)
PET Estimation Difficulty	[0 – 220]	107.83 (43.11)	109.10 (41.57)	125.77 (42.09)
Affective Appraisal				
UVI Humanness	[1 – 7]	3.87 (1.23)	3.89 (1.30)	4.03 (1.29)
UVI Eeriness	[1 – 7]	3.76 (0.98)	3.74 (0.99)	3.65 (1.03)
UVI Attractiveness	[1 – 7]	4.32 (1.05)	4.43 (1.19)	4.48 (0.97)
Distance Estimation				
Distance Estimation		0.84 (0.20)	2.25 (0.47)	3.64 (0.90)
Distance Misestimation		-0.17 (0.20)	-0.25 (0.47)	-0.36 (0.90)

Table C3.2: Descriptive values of our measures that were compared between the short (1 m), middle (2.5 m), and far (4 m) SODs.

significantly higher estimated distance for far compared to short, $Z = 4.790, p < .001, r = 0.875$, for far compared to middle, $Z = 4.732, p < .001, r = 0.864$, and for middle compared to short SOD, $Z = 4.810, p < .001, r = 0.878$. Hence, we accept H1.1 and consider our experimental manipulation as successful.

We further used the distance estimations to test whether a distance compression effect for our SODs occurred. Comparing the calculated distance misestimations between the SODs revealed no significant differences, $\chi^2(2) = 3.717, p = .156, W = 0.062$. Hence, we compared participants' distance estimates to the ground truth across all SODs and revealed a significant distance compression ($M = 11.8\,\%$, $SD = 20.69\,\%$) for our sample, $Z = 4.122, p < .001, r = 0.753$. Hence, we accept H1.2. The results are depicted in Figure C3.6.

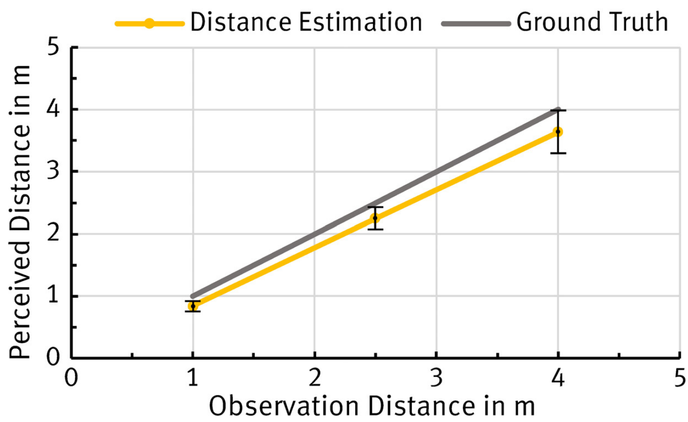

Figure C3.6: Distance estimations for our short (1 m), middle (2.5 m), and far (4 m) SODs in comparison to the ground truth. Error bars represent 95 % confidence intervals.

3.4.2 Sense of Embodiment, Self-Similarity, and Self-Attribution

Concerning the SoE, we compared VBO, agency, self-location, self-similarity, and self-attribution between our three SODs. The results revealed no significant differences between the conditions for VBO, $\chi^2(2) = 0.585, p = .746, W = 0.010$, agency, $\chi^2(2) = 3.089, p = .213, W = 0.051$, self-location, $F(2, 58) = 0.905, p = .410, f = 0.176$, self-similarity, $\chi^2(2) = 2.523, p = .283, W = 0.042$, and self-attribution, $\chi^2(2) = 0.925, p = .630, W = 0.015$. Hence, we reject our hypothesis H2.1 but do not discard H2.2 for now. We further found no significant correlations between the controls RSES and BSQ on any of the SoE factors.

3.4.3 Body Weight Perception

We compared the participant's current body weight misestimations $\overline{M}$ and $\overline{A}$, their ideal body weight estimations, and their estimations of the average body weight in the population between our three SODs using the AMT. The results revealed no significant difference between the conditions for the current body weight misestimations $\overline{M}$, $F(2, 58) = 0.802, p = .453, f = 0.167$, and for the body weight estimations of the ideal body weight, $\chi^2(2) = 2.4, p = .301, W = 0.040$, and the average body weight in the population, $\chi^2(2) = 4.2, p = .122, W = 0.070$. Based on the results for AMT, we do not reject H3.1 for now but reject H3.2. In addition, we explored whether the body weight estimations $\overline{M}$ accumulated across all conditions ($M = -0.48, SD = 3.6$) differed significantly from the actual body weight of the avatars. However, the calculated one-sample t-test showed no significant difference, $t(29) = 0.728, p = .472, d = 0.13$.

We further compared the participant's body weight misestimations $\overline{M}$ and $\overline{A}$ between our three SODs using the PET. We could neither find significant differences for body weight misestimations $\overline{M}$, $F(2, 58) = 0.72, p = .931, f = 0.002$, nor for absolute body weight misestimations $\overline{A}$, $\chi^2(2) = 2.467, p = .291, W = 0.041$, between the SODs.Based on the results for PET, we can also not reject H3.1 for now but reject H3.2. In addition, we explored whether the body weight estimations $\overline{M}$ accumulated across all conditions ($M = -0.22, SD = 6.5$) differed significantly from the actual body weight of the avatars. However, the calculated one-sample t-test showed no significant difference, $t(29) = 0.182, p = .857, d = 0.03$.

For the perceived body weight estimation difficulty, we found significant differences between SODs, $\chi^2(2) = 14.625, p = .001, W = 0.244$. Two-tailed Wilcoxon signed-rank post-hoc tests revealed a significantly higher difficulty for far compared to short, $Z = 3.133, p = .002, r = 0.572$, and for far compared to middle, $Z = 3.38, p = .001, r = 0.617$, but not between the short and middle SODs. Since we did not find significant differences between all conditions, we reject H3.3.

The calculated correlations for controlling the relationship between RSES and BSQ scores and the body weight misestimations $\overline{M}$ and $\overline{A}$ in AMT and PET, as well as the estimation difficulty in PET, are shown in Table C3.3. Since there was no significant difference in body weight estimates between SODs, we aggregated the dependent variables across conditions. We used the absolute values of $\overline{M}$ to operate on the sign-adjusted misestimations and not on sign-dependent under- or overestimations, possibly compensating for each other in a correlation. By calculating simple linear regressions for the significant correlations, we found that AMT Current $|\overline{M}|$ is significantly predicted by RSES, $F(1, 28) = 5.40, p = .023$, with an adjusted R^2 of .14 following the equation AMT Current$|\overline{M}| = 6.81 - 0.19 \cdot$ (RSES Score). We further found that the RSES significantly predicts the PET Estimation Difficulty, $F(1, 28) = 9.40, p = .005$, with an adjusted R^2 of .23 following the equation PET Estimation Difficulty $= 201.7 - 4.18 \cdot$ (RSES Score), and BSQ, $F(1, 28) = 4.62, p = .040$, with an adjusted R^2 of .11 following the equation PET Estimation Difficulty $= 69.17 + 0.57 \cdot$ (BSQ Score).

Measure	RSES	BSQ
AMT Current $\|\overline{M}\|$	$-.41^{*}$	.06
AMT Current $\overline{A}$	$-.23$	$-.22$
PET $\|\overline{M}\|$	.04	$-.28$
PET $\overline{A}$	.10	$-.33$
PET Estimation Difficulty	$-.50^{**}$	$.38^{*}$

Table C3.3: Correlations between RSES and BSQ scores and the body weight misestimations $\overline{M}$ and $\overline{A}$ in AMT and PET as well as the estimation difficulty in PET. Single-asterisks indicate significant and double-asterisks highly significant p-values.

3.4.4 Affective Appraisal

For the participant's affective appraisal of the avatar, we compared humanness, eeriness, and attractiveness between our three SODs. The results revealed no significant differences between conditions for humanness, $F(2,58) = 0.829, p = .441, f = 0.170$, eeriness, $F(2,58) = 0.488, p = .617, f = 0.017$, and attractiveness, $F(2,58) = 0.938, p = .397, f = 0.179$. Hence, we do not discard H4.1 for now but reject our hypothesis H4.2.

The calculated correlations between RSES and BSQ scores and the affective appraisal of the avatars can be found in Table C3.4. Since there were no significant differences in the affective appraisal, we aggregated the dependent variables across conditions. By calculating simple linear regressions for the significant correlations, we found that the BSQ scores significantly predict the perceived eeriness of the avatar, $F(1,28) = 4.83, p = .036$, with an adjusted R^2 of .12 following the equation UVI Eeriness $= 4.79 - 0.013 \cdot$ (BSQ Score). We further found that the RSES significantly predicts the perceived attractiveness of the avatar $F(1,28) = 5.28, p = .029$, with an adjusted R^2 of .13 following the equation UVI Attractiveness $= 2.63 + 0.85 \cdot$ (RSES Score).

Measure	RSES	BSQ
UVI Humanness	.13	.06
UVI Eeriness	.21	$-.38^{*}$
UVI Attractiveness	$.40^{*}$	$-.04$

Table C3.4: Correlations between RSES and BSQ and the different affective appraisal scores. Single-asterisks indicate significant p-values.

3.4.5 Simulator Sickness

We controlled whether there was a significant increase in simulator sickness-related symptoms during the VR exposures. Since the assumptions for parametric testing were not met for SSQ scores, we compared pre and post-measurements using a two-tailed Wilcoxon signed-rank test. The results showed that the scores did not differ significantly between pre ($M = 13.34, SD = 15.7$) and post-measurements ($M = 16.34, SD = 22.34$), $Z = 0.543, p = .587, r = 0.100$. Two participants showed an increase in the SSQ score above 20 points between pre and post-measurement but did not complain about the occurrence of symptoms or appear as outliers in other measurements. Therefore, we decided to keep them in our sample.

3.5 Discussion

Prior work has raised the question of whether distance-related biases in virtual mirror exposure scenarios influence the perception of an embodied avatar within a virtual environment (Wolf et al., 2022b, 2022c). Since the analysis of existing work allowed only limited conclusions, we systematically investigated the role of SOD on the embodiment and perception of avatars in a user study. Participants observed, manipulated, and rated their avatars in a short (1 m), middle (2.5 m), and far (4 m) distance between themselves and the virtual mirror. Our manipulation check (H1.1) showed a successful manipulation of the SOD, as participants estimated the distance to the mirror in the conditions significantly different. We could further confirm a significant distance compression effect in the distance estimations (H1.2). However, compared with the distance compression effect observed in other state-of-the-art consumer HMDs (Buck et al., 2018; Kelly, 2022; Kelly et al., 2022), the obtained distance compression of about 12 % in our study using the Valve Index was relatively small. A potential reason could be the compensating effect of the first-person perspective on the embodied avatar (Gonzalez-Franco et al., 2019; Leyrer et al., 2011; Mohler et al., 2010).

3.5.1 Sense of Embodiment, Self-Similarity, Self-Attribution

Our results for SoE, self-similarity, and self-attribution showed no significant differences between the SODs. This result is in line with H2.2 for agency and self-location, as previous work suggested that a change in the third-person perspective would have no significant influence on the measures as long as a first-person perspective is provided simultaneously (Debarba et al., 2017; Gorisse et al., 2017; Inoue & Kitazaki, 2021; Kilteni et al., 2012). With our study design and statistical power, we would have revealed medium to large effects but cannot rule out existing small effects. In addition, future research should show how the SOD would impact agency and self-location without presenting the presumed dominant first-person perspective.

We further could not confirm our H2.1, which assumes that the participant's feeling of VBO, self-similarity, and self-attribution will decrease with increasing SOD from the virtual mirror. Here, we expected initially that the increasing blurriness in the presentation of the avatar in the virtual mirror (c.f., Figure C3.1) would lead to a reduction of recognizable personal features (Tsakiris, 2008; Waltemate et al., 2018), which would ultimately affect participants' judgments. For the observed contrary results, we have a couple of potential explanations. First, a learning effect could have occurred since we used a within-subjects design in which each participant performed the tasks three times. After the exposure closer to the mirror, participants might have rated their avatar with the memorized details in mind. However, this is rather unlikely since our additional analysis of only the first run did not reveal any differences from the presented analysis. Second, participants knew they were facing their personalized avatar since they signed the informed consent and performed a body scan before the study. Hence, their perceived similarity to their avatar could result from a possible "placebo effect", i.e., the belief that they are facing their personalized avatar. However, to our knowledge, no systematic research on the influence of the user's expectation towards an avatar on the perceived SoE exists, and future work, including a control condition with non-personalized avatars, seems required. Third, recent work suggests that in some cases, experiencing an avatar exclusively from the first-person perspective may be sufficient to develop a similarly high feeling of VBO compared to having a third-person perspective, which would make the latter negligible (Bartl et al., 2022; Döllinger et al., 2023b). Other works consider the first-person perspective at least to be more dominant (Debarba et al., 2017; Gorisse et al., 2017). However, there is also work that assumes that providing the third-person perspective enhances the VBO significantly (Inoue & Kitazaki, 2021; Kilteni et al., 2012), especially when using personalized avatars (Waltemate et al., 2018). Future work on the general role of perspective in the embodiment of avatars on SoE seems necessary to resolve this ambiguity. The final, and in our opinion, most likely explanation is that the reduced resolution (e.g., at four meters about a quarter of the resolution of one meter), despite the obvious blurring (c.f., Figure C3.1), was still high enough for participants to recognize themselves without any limitations. For future work, it suggests validating our results with non-personalized generic avatars and even larger SODs above four meters.

3.5.2 Body Weight Perception

Prior to our study, we expected no differences between the SODs in the participant's body weight misestimations $\overline{M}$ as well as in the estimations for their ideal body weight and the guessed average body weight in the population (H3.1). However, we found no significant differences between the conditions. Considering that the distance compression did not significantly differ between SODs, the results are no surprise. Furthermore, since the body weight misestimations $\overline{M}$ did not differ significantly from the avatar's body weight, we assume that the observed distance compression of around 12 % had no impact on body weight estimations. Hence, we assume that the size-distance invariance hypothesis (Gilinsky, 1951) was violated, as already observed in other works (Brenner & van Damme, 1999; Kelly et al., 2018). The most likely explanation is the provided first-person perspective on the avatar, which could have served as a reference cue to correct body size estimations. However, our non-significant results do not mean that there is no possible effect but that we would have found at least medium and large effects based on our sensitivity analysis.

In contrast to $\overline{M}$, we expected that the absolute body weight misestimations $\overline{A}$, which served as an indicator of the uncertainty of the estimates (Wolf et al., 2022c), and the estimation difficulty would increase with increasing SOD (H3.2 and H3.3). We could not confirm our prior assumption for H3.2 since we could not find any significant differences in the measures for $\overline{A}$. This is partly contrary to the results of the perceived estimation difficulty (H3.3), for which we found a significant increase from middle to far SOD. Participants rated the body weight estimation more difficult for the longest distance, but the greater perceived difficulty did not result in higher absolute misestimations.

We further explored the influence of our control measures of self-esteem and body shape concerns on our body weight perception measures. We found that the participants' self-esteem significantly predicts their misestimation $\overline{M}$ of their current body weight in the AMT. The higher the self-esteem was, the more accurate the body weight estimates were. We further found a significant prediction of the participants' perceived body weight estimation difficulty by their self-esteem and body shape concerns. Estimations were perceived as more difficult when the body shape concerns were higher, and the self-esteem was lower. The results support assumptions of prior work that self-esteem and body shape concerns are linked to body image distortions (Irvine et al., 2019; Kamaria et al., 2016; O'Dea, 2012).

3.5.3 Affective Appraisal

As expected, we found no significant differences between SODs in participants' affective appraisal of the avatar in terms of perceived humanness (H4.1). However, against our expectations, we also found no significant differences regarding eeriness and attractiveness (H4.2). This is surprising since, based on the work of Döllinger et al. (2022c), we assumed that participants would perceive minor defects in reconstructing their personalized avatar to a lesser extent with increasing distance from the mirror and thus judge their avatar to be less creepy and more attractive. However, we observed a minor descriptive trend for both measures in the expected direction. The effect may only become apparent at even higher SODs, as already suspected for VBO, self-similarity, and self-attribution.

The investigation of our control variables concerning possible subjective predictors of the affective appraisal of the avatars revealed interesting insights. We found that the participants' perceived attractiveness of their avatars is significantly predicted by their self-esteem. The higher the self-esteem, the higher the perceived attractiveness of the avatar. Since it is well documented that the self-rating of one's physical attractiveness correlates with self-esteem (Kenealy et al., 1991; Patzer, 1995), we attribute this finding primarily to the avatars' personalization. However, other work has also suggested that personal characteristics can be attributed to non-personalized avatars via embodiment (Wolf et al., 2021), leaving space for further investigation. Furthermore, we found a significant prediction of the participants' perceived eeriness of the avatar by their body shape concerns. The higher the body shape concerns, the lower the perceived eeriness. A possible reason for this could be that participants who are concerned about their body shape tend to focus their attention on the parts of their personalized avatar that bother them on their real body rather than on areas that are irregularly reconstructed (Bauer et al., 2017; Tuschen-Caffier et al., 2015). Future work investigating the perception of avatars, especially when using personalized avatars or between-subject designs, should consider self-esteem and body shape as covariates. In addition, further research is required to clarify the role of self-esteem and body concerns in the perception of avatars.

3.5.4 Practical Implications

Our study provides interesting insights that also have implications for the practical application of avatar embodiment in research and beyond. Our results show that it is rather unlikely that a systematic distance-related bias affects the sense of embodiment, perception of body weight, or affective appraisal of a personalized embodied avatar in VR mirror exposure in a SOD range between one and four meters. What may seem rather uninteresting from a scientific point of view, namely that our priorly expected differences could not be shown at the distances we selected, is of great use for practical application. For studies that neglected the SOD, it can be retrospectively assumed that it is unlikely that uncontrolled distances within our tested range had a confounding effect. Based on our results, we formulate the following practice guideline.

Guideline

> The distance between a personalized embodied avatar and a virtual mirror can be freely chosen in a range of one to four meters without expecting a major influence on the avatar's perception.

Nevertheless, with our statistical power, we can not entirely rule out small effects. The question remains how relevant these would be in a practical application compared to other individual-, system- or application-related influences. Given the limitations of our work stated below, we recommend that the avatar perception should always be carefully evaluated before the application in a practical context. This counts especially for serious applications in mental health or related areas, where it is vital to rule out or control unwanted distortions in the user's perception of the provided stimuli due to system- and application-related factors.

3.5.5 Limitations and Future Work

Throughout our discussion, we already identified some limitations of our work, which we summarize below and from which we derive future work. First, our work used photorealistically personalized avatars solely, limiting our findings to their use. Participants were fully aware that they got scanned, which might have biased their answers on self-recognition-related measures because one is usually aware of the own physical appearance. This could also have played a role in estimating body weight as in reality learned proportions of the own body could have also been applied to the avatar. Therefore, the influence of SOD should also be evaluated with non-personalized avatars.

Second, we can state that our experimental manipulation of the SOD between one and four meters was unlikely to cause differences in our measures. However, we can not rule out differences occurring on larger distances where a distance compression might be more pronounced, and the avatars' rendering resolution declines even more. But this limitation might only be relevant from a theoretical point of view, since a distance of four meters between the observer and the mirror is unlikely to be exceeded in the practical application of virtual mirrors. Since resolution and distance compression are bound to particular HMDs (Angelov et al., 2020; Kelly, 2022), it appears necessary to either repeat our investigation with different HMDs or extend it to investigate each particular property on its own. For example, the avatar rendering could artificially be reduced while the distance to the mirror is kept constant. For this purpose, the method of an interactive controllable mirror, as suggested by Bartl et al. (2021b), extended to a dynamic adjustable mirror resolution, could be used. However, as long as the causes for device-specific differences, e.g., in body weight perception (Wolf et al., 2022b, 2022c), are not precisely clarified, a device-related assessment still seems necessary.

Third, we provided the user simultaneously with a first-person and a third-person perspective in our virtual environment. However, the first-person perspective could have corrected potentially stronger distance-related biases, as described by prior work (Leyrer et al., 2011; Mohler et al., 2010; Renner et al., 2013; Ries et al., 2008). For use cases where the avatar is only provided in a third-person perspective but without a mirror or embodiment (Thaler, 2019; Wolf et al., 2022c), the observation distance on the avatar could have a different impact. Future work should investigate the role of observation distance without embodiment or a first-person perspective.

3.6 Conclusion and Contribution

Avatar embodiment in VR has steadily increased in recent years and is likely to grow further due to technological advancements. Especially in the field of serious applications, the question arises of how the avatar embodiment affects the user's perception and by what factors an effect is influenced. Our study contributes to answering this question by investigating the influence of the self-observation distance (SOD) when looking at one's own embodied avatar in a virtual mirror. We found that the SOD in avatar embodiment scenarios using a virtual mirror does not influence the sense of embodiment, body weight perception, and affective appraisal towards the avatar in a distance of one to four meters when the first-person perspective is presented simultaneously. Therefore, we conclude that distance compression and a distance-related reduced resolution of the third-person representation of the avatar do not affect the perception of personalized avatars in the tested range. Although our results need to be verified and confirmed for different use cases, we assume that the outcomes apply to most current applications employing avatar embodiment and virtual mirror exposure. Hence, we assume that recent avatar embodiment or perception research is unlikely to be subject to an uncontrolled distance-related systematic bias within our tested SOD range.

Conflict of Interest Statement

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Data Availability Statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics Statement

The studies involving human participants were reviewed and approved by Ethics Committee of the Institute Human-Computer-Media (MCM) of the University of Würzburg. The participants provided their written informed consent to participate in this study.

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Author Contributions

Erik Wolf conceptualized large parts of the experimental design, collected the data, performed the data analysis, and took the lead in writing the manuscript. Erik Wolf and David Mal developed the Unity application, including the experimental environment and avatar animation system. Nina Döllinger supported the data analysis. Mario Botsch and Stephan Wenninger provided the framework for the reconstruction of the avatars as well as their integration and realistic body weight modification in Unity. Andrea Bartl supported the generation of avatars and data collection. Carolin Wienrich and Marc Erich Latoschik conceived the original project idea, discussed the study design, and supervised the project. All authors continuously provided constructive feedback and helped to shape the study and the corresponding manuscript [7].

[7] The author contributions of the original paper were refined in the course of the dissertation to highlight each author's contribution further.

Chapter 4

Exploring Presence, Avatar Embodiment, and Body Perception with a Holographic Augmented Reality Mirror

This chapter has been published as follows:[1]
Wolf, E., Fiedler, M. L., Döllinger, N., Wienrich, C., & Latoschik, M. E. (2022b). Exploring presence, avatar embodiment, and body perception with a holographic augmented reality mirror. *2022 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, 350–359. https://doi.org/10.1109/VR51125.2022.00054x

Figure C4.1: The picture shows a participant embodying a generic avatar and observing it in the holographic mirror. In our evaluation, participants had to perform body movements, answer questions about the experience, and guess the body weight of the avatar.

[1] As part of the dissertation, the published text was editorially revised, with only slight orthographic, stylistic, and formal adjustments, while completely retaining the original semantics.

Abstract

The embodiment of avatars in virtual reality (VR) is a promising tool for enhancing the user's mental health. A great example is the treatment of body image disturbances, where eliciting a full-body illusion can help identify, visualize, and modulate persisting misperceptions. Augmented reality (AR) could complement recent advances in the field by incorporating real elements, such as the therapist or the user's real body, into therapeutic scenarios. However, research on the use of AR in this context is very sparse. Therefore, we present a holographic AR mirror system based on an optical see-through (OST) device and markerless body tracking, collect valuable qualitative feedback regarding its user experience, and compare quantitative results regarding presence, embodiment, and body weight perception to similar systems using video see-through (VST) AR and VR. For our OST AR system, a total of 27 normal-weight female participants provided predominantly positive feedback on display properties (field of view, luminosity, and transparency of virtual objects), body tracking, and the perception of the avatar's appearance and movements. In the quantitative comparison to the VST AR and VR systems, participants reported significantly lower feelings of presence, while they estimated the body weight of the generic avatar significantly higher when using our OST AR system. For virtual body ownership and agency, we found only partially significant differences. In summary, our study shows the general applicability of OST AR in the given context offering huge potential in future therapeutic scenarios. However, the comparative evaluation between OST AR, VST AR, and VR also revealed significant differences in relevant measures. Future work is mandatory to corroborate our findings and to classify the significance in a therapeutic context.

Keywords

Virtual reality, virtual human, virtual body ownership, agency, body image distortion, body weight perception

4.1 Introduction

The use of embodied avatars (i.e., 3D models of human beings controlled by the user), or so-called full-body illusions, for behavioral manipulation has become a hot topic in virtual reality (VR) research (Wienrich et al., 2021a). Since the discovery of the Proteus effect (Yee & Bailenson, 2007), suggesting that an avatar's appearance can influence its user's attitudes and behavior, various works have demonstrated the beneficial capabilities of full-body illusions in general (Ratan et al., 2020), but also for mental health (Matamala-Gomez et al., 2021). Great examples are eating and body weight disorders with an underlying body image distortion, where the potential of full-body illusions has recently been confirmed (Turbyne et al., 2021). The general idea of improving body image through modulated embodied avatars can be realized by scenarios helping to reveal and visualize the users' mental body image, improving the motivation for therapy by showing their weight loss successes, or working intensively with their current and desired body weight (Döllinger et al., 2019; Riva et al., 2019).

However, VR usually shuts out the visual perception of the real environment. By breaking the users' isolation in the virtual environment through augmented reality (AR), they could reference the experience directly to their physical bodies. For example, an exposure would be conceivable in which users can compare their virtual self in a virtual mirror with themselves in a real mirror by only looking in a different direction. AR would also allow for a multimodal interaction between therapists and users, enabling better intervention when necessary. However, while the use of embodied avatars in VR has become widespread, the application in AR is far less common, and the display technology's influence on user experience related factors and potentially relevant treatment effect mediators such as the feeling of presence and embodiment or body weight perception has not been clarified yet (Genay et al., 2021; Wienrich et al., 2021a; Wolf et al., 2020). Hence, the question arises whether the potential advantages of AR are accompanied by an unintended impact on the aforementioned factors.

In our work, we have developed a holographic AR mirror system for investigating presence, avatar embodiment, and body weight perception in AR. It is based on a Microsoft HoloLens 2 (Microsoft, 2019a) optical see-through (OST) AR headset and markerless body tracking provided by The Captury (Captury, 2021; Stoll et al., 2011), allowing users to interact with their physical bodies in an unrestricted way. Within the holographic mirror, they observe a generic photorealistic avatar animated according to their movements, giving them the feeling of embodying it. To evaluate the general quality of our OST AR system, we performed qualitative interviews on the perception of the avatar's appearance and movements, including questions about the perceived accuracy of body tracking and the display properties (e.g., field of view (FOV), luminosity, or resolution). To evaluate the strength of potential effect mediators quantitatively, we captured the feeling of presence and embodiment and asked for estimations of the avatar's body weight. We further controlled self-esteem, body shape concerns, gender, simulator sickness, and the participant's body mass index (BMI) as potential confounds. In an extended statistical analysis, we compared the quantitative results of our OST AR system to the video see-through (VST) AR and VR systems tested in previous work (Wolf et al., 2020).

4.2 Related Work

Milgram's reality-virtuality continuum states that different display types offer different degrees of virtuality depending on their characteristics (e.g., reality covered by virtual elements (AR) or solely virtual elements (VR), Milgram et al., 1995). These characteristics are often associated with the degree of immersion as introduced by Slater and Wilbur (1997), defining the degree of virtual reality on a display's objective properties (e.g., FOV, luminosity, or resolution, Slater, 2018). A higher immersion usually provides a higher level of virtuality. In our context, the spectrum ranges from low immersive OST AR displays, over more immersive VST AR displays, to fully immersive VR displays, which all offer different kinds of user experiences (Wienrich et al., 2021b).

A major concept quantifying the quality of the provided experience is presence, originally defined as the sense of really being in a virtual environment and later divided into place and plausibility illusion (Slater, 2009). Wienrich et al. (2021b) recently elaborated the sense of transportation (or spatial presence), known as place illusion and determined by the system's immersion, and the sense of realism, known as plausibility illusion and determined by the experience's coherence, as two major dimensions for quantifying presence across the reality-virtuality continuum. A higher immersion of a display usually results in a higher feeling of presence (Chicchi Giglioli et al., 2019; Cummings & Bailenson, 2016; Waltemate et al., 2018), and consequently to a higher degree of plausibility and credibility of the experience, which has been suggested as a necessary "hygiene factor" for behavior change in mental health using AR or VR (Krijn et al., 2004; Rothbaum, 2006; Wienrich et al., 2021a).

Another important quale of the user's experience in terms of behavioral changes initiated by the Proteus effect is the sense of embodiment. It can be decomposed into the feeling of being inside (self-location), controlling (agency), and having a virtual body (virtual body ownership (VBO), Kilteni et al., 2012; D. Roth & Latoschik, 2020). Similar to Milgram's reality-virtuality continuum, Genay et al. (2021) recently proposed the body avatarization continuum, which encompasses the extent to which a user embodies a virtual representation. It ranges from having a real body, over having a partial virtual body representation, to being fully embodied to a virtual avatar. Similar to the relation of immersion and presence, it can be assumed that the degree of body avatarization, often determined or limited by the used display type and its immersion, impacts the feeling of embodiment (Genay et al., 2021). For example, seeing the real body while also having a virtual body can lead to a direct comparison of the bodies and thus might decrease VBO, as observed in other works (Škola & Liarokapis, 2016; Waltemate et al., 2018). A narrowed FOV could also have a negative impact on VBO, as it might break the continuity of the embodiment experience (Genay et al., 2021). Particularly when using OST AR displays, the direct visual feedback of the real body movements might impact agency since there is no latency in the view on the real body, increasing the latency between directly observed real motions and the virtual body's motions (Genay et al., 2021). Similarly, the direct view on the real body ensures that the visual and proprioceptive information is synchronized (Rolland & Fuchs, 2000), but this consequently results in a greater visual and proprioceptive difference between the real and the virtual body. Lastly, virtual content in OST AR is partially transparent and might cause depth perception problems that could negatively affect the embodiment experience (Wang et al., 2017).

Ratan et al. (2020) assume that "the Proteus effect outcomes should be stronger the closer the user feels to the avatar", which might not be the case when the feeling of embodiment decreases due to the use of AR. However, the influence of the display type on the feeling of embodiment has been rarely investigated empirically (Genay et al., 2021). Škola and Liarokapis (2016) examined the feeling of VBO in response to a real-world, AR, and VR condition and found a significant difference between the AR and real-world conditions, but not between AR and VR. Wolf et al. (2020) investigated how the type of display (VST AR vs. VR) affects embodiment and presence and found that the influence was rather small. The authors referred to the fairly small difference in immersion as an explanation. Finally, Nimcharoen et al. (2018) developed an OST AR embodiment system using 3D point cloud avatars and explored presence and embodiment. They were able to show that participants developed a considerable feeling of VBO and agency towards their avatar but did not include a comparative condition, making interpretation difficult and showing us that comparative conditions are inevitable for our work.

With respect to body image, the user's perception of the virtual avatar's body weight is another aspect to consider. Prior work has already shown that avatar embodiment impacts body weight perception based on the user's BMI (Wolf et al., 2021). However, the influence of different display types on body weight perception seems unclear. Wolf et al. (2020) conducted a narrow review of potential factors influencing body perception in AR and VR and found that existing work is still rare and heterogeneous, preventing them from determining the influence of different display types on body weight perception. In their additionally performed evaluation, they found no significant difference in body weight estimates between VST AR and VR, but observed descriptive differences, based on which they did not rule out an influence of display type on body weight perception.

In summary, the introduced potential benefit of AR, being able to interact with the real world, could be accompanied by a diminished feeling of presence and embodiment, negatively impacting on the users' experience. In addition, it is mainly unclear how different display technologies alter the user's body weight perception concerning body image therapy.

Due to only little empirical work on body illusions in AR, a comparison of different display technologies concerning presence, embodiment, and body weight perception seem essential to further explore the use of body illusions in AR, especially with regard to a future use in the field of mental health.

4.3 System Description

Our holographic AR mirror system was developed using *Unity* 2020.3.11f1 LTS (Unity Technologies, 2020). It renders a virtual mirror hologram on a wall in front of the user, showing a generic avatar as the user's mirror image being animated by the user's captured movements in real-time (see Figure C4.1). At the same time, the user can observe the real environment and the own physical body. The laboratory where the user was located during our evaluation was recreated as a 3D model to render a plausible background in the holographic AR mirror. As an AR display, we used the *Microsoft HoloLens 2* (Microsoft, 2019a), providing the user a resolution of 1440×936 px with a FOV in horizontal of $43°$ and in vertical of $29°$ and a refresh rate of 60 Hz. In our evaluation, the HoloLens 2 was connected via 100 MBit/s ethernet to a high-end PC composed of an *Intel Core i7-9700K*, an *Nvidia RTX2080 TI*, and *32 GB RAM* running *Windows 10* and used to render the content via *Holographic Remoting*. In the following, we will explain how the user's movements are captured in order to animate the avatar as the user's virtual mirror image. A video showing the running application is provided in the supplementary material.

4.3.1 Motion Tracking and Avatar Animation

For motion tracking, we use the markerless tracking system *Captury Live* (Captury, 2021; Stoll et al., 2011). Eight *FLIR Blackfly S BFS-PGE-16S2C* RGB cameras mounted on the ceiling of our laboratory running at a capturing rate of 100 Hz assure that the user can be tracked in the whole laboratory in real-time (see Figure C4.2). The cameras are connected via two 4-port 1 GBit/s ethernet frame-grabber to a powerful PC composed of an *Intel Core i7-9700K*, an *Nvidia RTX2080 TI*, and *32 GB RAM* running *Ubuntu 18* and Captury Live. The system delivers a stable body pose via ethernet that can be streamed directly into Unity using The Captury's Unity plug-in. The body pose is then calibrated in a way that the head always follows the HoloLens 2 on the horizontal axes without drifting. A huge drawback of the current version of the tracking system is the provided quality of the hand tracking, which is in rotation restricted to only two degrees of freedom. Therefore, we decided to use the built-in hand tracking of the HoloLens 2 in addition. The hand movements are tracked with suffi-

Figure C4.2: The screenshot of Captury Live's tracking view shows the user from Figure C4.1 inside our laboratory currently waving to her holographic reflection while her pose is tracked in real-time.

cient accuracy (considering the distance to the mirror, Soares et al., 2021), on all six degrees of freedom, and in real-time as soon a hand is held into the sensory field of the device (see Figure C4.3).

The body pose received from Captury Live is continuously retargeted to the avatar shown in the mirror, which is automatically scaled to the user's body height. The potentially occurring discrepancies between the received skeleton and the generic skeleton of the displayed avatar (e.g., different limb lengths) reflected in inaccuracies in the alignment of the pose or the end-effectors (hands and feet) are compensated by an IK-supported pose optimization step, where the end-effectors of the avatar are aligned with the end-effectors of the tracked user. This leads to high positional conformity between the user's body and the embodied

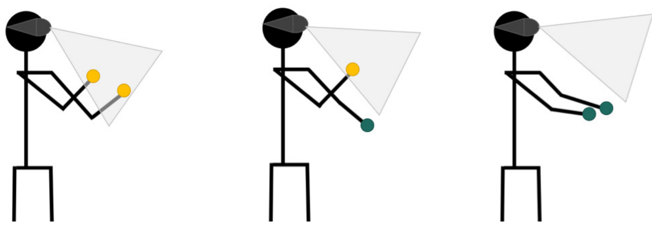

Figure C4.3: The pictures sketches the principles of our hand tracking. The light gray area in front of the head visualizes the sensory field of the HoloLens 2. As soon a hand is in the field, the position and orientation is taken from the HoloLens 2 hand tracking (yellow dot), otherwise, it is captured via Captury Live (green dot).

avatar and avoids sliding feet due to the retargeting process. The end-effector adaptions are also used to integrate the hand pose of the HoloLens 2 hand tracking into the avatar's pose. As soon as a hand is recognized in the sensory field of the HoloLens 2 hand tracking, the corresponding hand of the avatar interpolates from the Captury to the HoloLens 2 hand tracking and vice versa. The interpolation time was empirically determined to 100 ms, providing a smooth transition between the two tracking systems and avoiding choppy hand movements.

In a further step, we used frame-counting (He et al., 2000) to determine the motion-to-photon latency of our virtual mirror image. For this purpose, a high-speed camera of an *iPhone 12* was used to record the user's motions and the corresponding reactions of the avatar through the see-through display at 240 fps. The motion-to-photon latency for the whole body pose from Captury averaged 162.4 ms ($SD = 30.39$ ms). For the HoloLens 2 hand tracking, the latency averaged 126.5 ms ($SD = 18.94$ ms). We attribute the generally high latency to the use of Holographic Remoting, which unfortunately was unavoidable for performing our evaluation. However, for future prototypes, a reduction of latency seems feasible.

4.4 Evaluation

We tested our holographic AR mirror system in a structured evaluation using several qualitative questions and quantitative measurements. Our experimental setup followed our previous work (Wolf et al., 2020) in order to enable the most valid comparison possible between the newly collected data of the OST AR condition and the already existing data of the VST AR and VR conditions from the previous work. The used avatar was originally created using the generation pipeline of Achenbach et al. (2017).

4.4.1 Participants

We included 27 female-only BA students from the University of Würzburg in our evaluation that fulfilled the following participation requirements: (1) they had to have good or corrected to normal vision and hearing; (2) they had to have at least ten years of experience with the German language; (3) they should currently not suffer from a diagnosed mental, psychosomatic, or body weight disorder; (4) they should not have a known sensitivity to simulator sickness; (5) and they should not have participated in the study of the previous work. Since body weight perception might differ between gender (Connor-Greene, 1988), we followed Wolf et al. (2020) and only tested females. One additional participant was excluded due to technical issues. Descriptive values and statistical analysis regarding relevant demographic data and control measurements will be provided in the results section.

4.4.2 Design and Hypotheses

We employed an experimental design that combines the data collected in this evaluation (OST AR) with the data previously collected (VST AR and VR, Wolf et al., 2020). Consequently, a 3×1 between-design with the *display type* being the independent variable was used. The display type could either be our OST AR display or their VST AR or VR display. The dependent variables were divided into the perceived feeling of *presence* and *embodiment* and *body weight misestimation* (BWM) of the avatar's BMI in relation to the avatar's real BMI. To support the post-hoc interpretation of the collected quantitative data, we additionally conducted supplemental interviews with focus on the OST VR system properties.

Based on our introduced related work, we propose the following hypotheses regarding our dependent variables. Since the results of our previous work have already been published (Wolf et al., 2020), we always formulate the hypotheses from the perspective of our OST AR condition with respect to the VST AR and VR conditions. All hypotheses are backed up by a brief summary of the relevant related work.

Due to the system properties of the OST AR display (i.e., narrow FOV, lower resolution and luminance, direct visibility of the real environment, virtual objects occlusion), we assume that our OST AR potentially provides a lower degree of immersion, which is known to impact negatively on presence (Chicchi Giglioli et al., 2019; Cummings & Bailenson, 2016; Skarbez et al., 2017; Waltemate et al., 2018). Therefore, we formulate the hypothesis regarding presence as follows.

Hypothesis

H1.1: Participants using OST AR will report a lower feeling of presence than participants using VST AR or VR.

As comprehensively summarized by Genay et al. (2021), the implementation of avatar embodiment in AR can negatively impact the feeling of embodiment. The physical body's presence can lead to a direct comparison with the virtual replica and thus might decrease VBO, as already observed in other works (Škola & Liarokapis, 2016; Waltemate et al., 2018). The direct availability of the physical body in OST AR can also influence agency, since there is no motion-to-photon latency in the view on the own physical body, which in turn increases the latency between directly observed physical motion and virtual motion observed in the mirror (Genay et al., 2021). Hence, we propose the following hypotheses:

Hypotheses

H2.1: Participants using the the OST AR will report a lower feeling of VBO towards their avatar than participants using the VST AR or VR.

H2.2: Participants using the OST AR will perceive a lower feeling of agency towards their avatar than participants using the VST AR or VR.

Based on the narrow review on body weight perception influencing factors performed by Wolf et al. (2020) and the results of their evaluation, we expect that body weight estimations could be influenced when using OST AR. However, since previous work is still rare and heterogeneous, we have refrained from formulating a directed hypothesis and decided to explore body weight estimations further. Our undirected hypothesis is as follows:

Hypothesis

H3.1: Participants using OST AR will estimate the avatar's body weight differently than participants using VST AR or VR.

4.4.3 Measurements

In the following, we summarize the questionnaires used to operationalize our variables, explain how body weight estimates were calculated, and describe the interview conducted.

Questionnaires

Table C4.1 summarizes all questionnaires used in our evaluation, including their different dimensions and original score ranges used for statistical analysis. The table further contains references to used validated German versions when available. Otherwise, we translated the questions to the best of our knowledge using back and forth translations. The time a questionnaire was conducted is depicted in Figure C4.4. For a comprehensive explanation of the measurements, we refer to corresponding publications. To allow for a comparison between different measurements, the values for presence and embodiment are presented in a normalized range from 0 to 10. For measuring presence, the participants received the additional information that virtual objects, such as the mirror, including its background, are counted as the virtual environment.

Questionnaire	Range	Measurement
Presence		
One-item (Bouchard et al., 2004, 2008)	[0 – 10]	General presence (GP)
IPQ (Schubert et al., 2001)	[0 – 6]	General presence (GP)
	[0 – 6]	Spatial presence (SP)
	[0 – 6]	Involvement (INV)
	[0 – 6]	Realism (REAL)
Embodiment		
One-item (Kalckert & Ehrsson, 2012; Waltemate et al., 2018)	[0 – 10]	Body ownership (VBO)
	[0 – 10]	Agency (AG)
VEQ (D. Roth & Latoschik, 2020)	[1 – 7]	Body ownership (VBO)
	[1 – 7]	Agency (AG)
Control		
SSQ (Bimberg et al., 2020; Kennedy et al., 1993)	[0 – 236]	Simulator sickness
BSQ (Cooper et al., 1987; Evans & Dolan, 1993; Pook et al., 2002)	[0 – 204]	Body shape concerns
RSES (Ferring & Filipp, 1996; Rosenberg, 2015; M. Roth et al., 2008)	[0 – 30]	Self-esteem

Table C4.1: Summary of all questionnaires used in our evaluation.

Body Weight Estimation

For each participant, body weight and height were captured using calibrated medical equipment. Subsequently, the participant's BMI was calculated as $\frac{\text{Body Weight in kg}}{(\text{Body Height in m})^2}$ (World Health Organization, 2019). Additionally, participants estimated the body weight of their uniformly scaled and height-matched avatar, from which we calculated the avatars' estimated BMI (E-BMI). We further calculated the avatars' approximated BMI (A-BMI) by multiplying the scaling factor s, which was calculated by dividing the participant's body height by the height of unscaled avatar, with the avatars original BMI. Body weight misestimation (BWM) further was calculated as $\frac{(\text{E-BMI}-\text{A-BMI})}{\text{A-BMI}}$. A negative value of BWM represents an underestimation of the avatar's body weight, and a positive value an overestimation. A detailed explanation of the calculations can be found in Wolf et al., 2020, Section 4.2.3.

Interview

A semi-structured interview with predefined questions was conducted to obtain information about the system's perceived quality and the AR experience itself. Especially the perception of the avatar's appearance and movement was in focus, including questions about the perceived accuracy of body tracking. However, possibly as negative interpretable display properties of the HoloLens 2, such as the perceived FOV or the perceived luminosity and transparency of the virtual objects, were also queried. A list of all questions can be found in the supplementary material of this work.

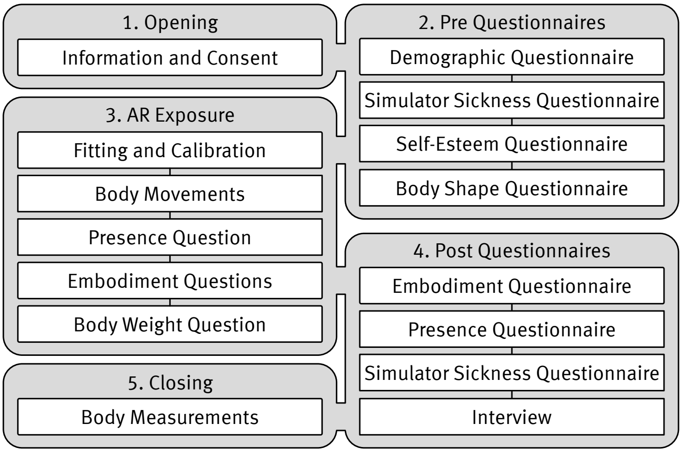

Figure C4.4: The figure shows the evaluation's procedure arranged in a meandering pattern including all questionnaires carried out.

4.4.4 Procedure

Figure C4.4 illustrates the procedure of an evaluation session that averaged 36 min per participant and took place in a quiet laboratory at the University of Würzburg. Before the evaluation, participants were required to read the COVID-19 regulations, privacy policy, and study information and to give explicit consent to participate. All questionnaires outside the AR exposure had to be completed on a separate computer in the laboratory using LimeSurvey 4 (LimeSurvey GmbH, 2020).

The subsequent AR exposure phase followed a pre-programmed logic, and participants automatically received all information via pre-recorded audio and visual text instructions. For calibration of the AR exposure, participants first had to walk a short distance in the laboratory to set up and optimize the markerless body tracking. Then, they put on the prepared and calibrated HoloLens 2 and had to remain standing for a brief moment to set up the avatar embodiment. At the end of the preparation, the experimenter verified that the system worked correctly. After the calibration, the virtual mirror appeared, and participants could see their virtual self. Subsequently, participants had to perform five movement tasks (i.e., waving towards the mirror image with left and right hand each, walking in place, circling the arms in front of the body, and performing hip movements while stretching the arms to both sides) while seeing their virtual representation in the mirror to strengthen the feeling of embodiment towards their avatar. This was followed by the one-item questions for presence and embodiment and the avatar's body weight. The AR exposure duration averaged 7.5 min.

After exposure, the participants completed the remaining questionnaires and the experimenter conducted the interview to collect the qualitative feedback. The interview duration averaged 6 min. Finally, the participants' weight and height were measured.

4.5 Results

The statistical analysis was performed using *R* version 4.0.5 (R Core Team, 2020). For sensitivity analysis, we used *G*Power* version 3.1.9.7 (Faul et al., 2009). Before analyzing our dependent variables, we first compared the three groups in terms of their homogeneity in relevant demographics and control measurements using a one-way between-subject ANOVA. The results a summarized in Table C4.2. Although we found a significant difference in age, we considered the maximum age difference of $\Delta M = 2.6$ as not relevant. For the remaining variables, we did not find any significant differences. Since SSQ values decreased in all conditions over time, we refrained from calculating tests between pre and post-measurements. All data are available on request.

	OST AR	VST AR	VR	
Measure	M (SD)	M (SD)	M (SD)	p
Age	22.3 (1.9)	20.3 (2.4)	19.7 (1.1)	$< .001^*$
BMI	22.5 (2.6)	22.1 (3)	22.4 (2.9)	.881
RSES	24.0 (3.9)	22 (4.4)	22.9 (4.7)	.253
BSQ	85.2 (23.9)	80.0 (26.4)	79.6 (26.0)	.668
Pre SSQ	22.6 (17.7)	26.5 (24.5)	16.6 (14.0)	.173
Post SSQ	19.7 (18.4)	22.4 (22.0)	14.1 (16.5)	.272

Table C4.2: The table shows the descriptive values as well as the statistical test results of the control variables between our groups. Asterisks indicate significant p-values.

4.5.1 Quantitative Measurements

By using non-normalized values, we calculated two planned contrasts for each variable of presence, embodiment, and body weight estimation within a one-way between-subject ANOVA model, comparing OST AR to either VST AR or VR. While all variables met the assumption of homoscedasticity within the ANOVA model, not all variables met the normality of residuals as a criterion for parametric tests. Nonetheless, one-way ANOVA is stated robust against violations of the assumption of normality given equal group sizes, and group sizes $n > 10$ (Blanca Mena et al., 2017). Since our experiment met those requirements and a

	OST AR	VST AR	VR
Measure	M (SD)	M (SD)	M (SD)
Presence			
One-item GP	4.85 (2.01)	6.22 (1.80)	6.74 (1.53)
IPQ GP	4.94 (1.93)	6.23 (2.47)	7.10 (1.99)
IPQ SP	4.90 (1.80)	6.30 (2.03)	7.20 (1.24)
IPQ INV	3.77 (2.01)	3.66 (1.68)	4.63 (1.91)
IPQ REAL	3.61 (1.39)	4.57 (1.40)	4.72 (0.83)
Embodiment			
One-item VBO	4.48 (1.89)	4.52 (2.49)	4.93 (2.23)
VEQ VBO	4.10 (1.94)	4.81 (2.32)	5.34 (2.00)
One-item AG	6.93 (1.47)	7.7 (1.75)	8.00 (1.39)
VEQ AG	7.84 (1.10)	8.26 (1.32)	8.24 (0.91)
Body Weight Estimation			
BWM	1.57 (6.96)	-6.92 (11.46)	-3.08 (8.69)

Table C4.3: The table shows the normalized descriptive values in a range from 0 to 10 (except BWM) for each measurement per condition.

cross-check with the results of the non-parametric Kruskal-Wallis test revealed no difference in findings, we decided to report the results of parametric testing for all variables for reasons of clarity. All descriptive values are shown in Table C4.3.

For a further exploratory examination, we calculated a multiple linear regression to predict body weight estimations based on centered participants' BMI and condition (OST AR vs. VST AR vs. VR). The model met all criteria for parametric testing. All tests were performed against an α of .05.

Presence

Confirming hypothesis H1, participants using OST AR reported significantly lower general presence in the one-item question than participants using VST AR, $t(78) = 2.81, p = .006, d = 0.72$, or VR, $t(78) = 3.87, p < .001, d = 1.06$. For IPQ, participants in the OST AR condition reported lower scores for general presence, $t(78) = 2.22, p = 0.029, d = 0.58$ (IPQ GP), spatial presence, $t(78) = 2.97, p = 0.004, d = 0.73$ (IPQ SP), and realism, $t(78) = 2.53, p = 0.013, d = 0.69$ (IPQ REAL) than in the VST AR condition, but not for involvement, $t(78) = 0.22, p = 0.833, d = 0.06$ (IPQ INV). Similarily, they stated lower ratings for general presence, $t(78) = 3.70, p < 0.001, d = 1.10$, spatial presence, $t(78) = 4.89, p < 0.001, d = 1.48$, and realism, $t(78) = 2.94, p = 0.004, d = 0.80$ in

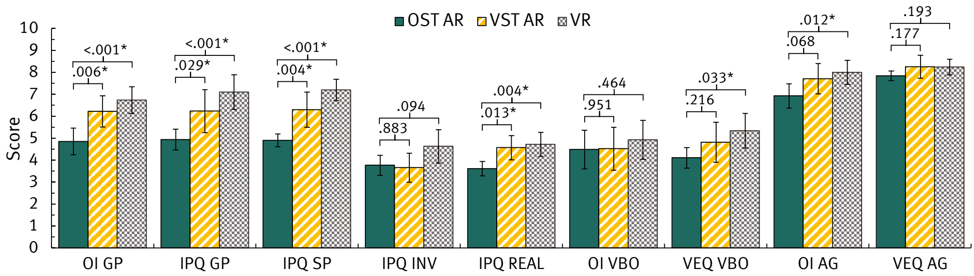

Figure C4.5: The bar chart shows the results of presence, VBO, and agency for all conditions normalized to a range from 0 to 10 together with the corresponding p-values. Error bars represent 95 % confidence intervals. Asterisks indicate significant p-values.

the OST AR condition compared to the VR condition. Again, involvement did not differ significantly between the conditions, $t(78) = 1.70, p = 0.094, d = 0.45$. Results are shown in Figure C4.5, left.

Embodiment

Contrary to hypothesis H2.1, the results of the one-item question for VBO did not differ significantly between OST AR and VST AR condition, $t(78) = 0.06, p = 0.951, d = 0.02$, and between OST AR and VR condition, $t(78) = 0.74, p = 0.464, d = 0.21$. Similarly, there was no significant difference in the VEQ ratings on VBO between OST AR and VST AR, $t(78) = 1.25, p = 0.216, d = 0.33$. However, OST AR and VR differed significantly in VEQ VBO, $t(78) = 2.17, p = 0.033, d = 0.63$. Results are shown in Figure C4.5, middle.

The one-item question results for agency did not differ significantly between OST AR and VST AR condition, $t(78) = 1.85, p = 0.068, d = 0.48$, but differed significantly between OST AR and VR condition, $t(78) = 2.56, p = 0.012, d = 0.75$. However, VEQ ratings on agency revealed neither significant difference between OST AR and VST AR, $t(78) = 1.36, p = 0.177, d = 0.34$, nor between OST AR and VR, $t(78) = 1.31, p = 0.193, d = 0.40$. Results are shown in Figure C4.5, right.

A sensitivity analysis revealed that a t-test in our ANOVA-model with a group sizes of $n = 27$ and an α-level of .05 would have revealed medium effects of $d = 0.78$ or greater with a power of .80 (Cohen, 2013). As the non-significant effect size d ranged between $d = 0.02$ and $d = 0.80$, we cannot completely discard a small effect of the condition on the perceived body ownership or agency.

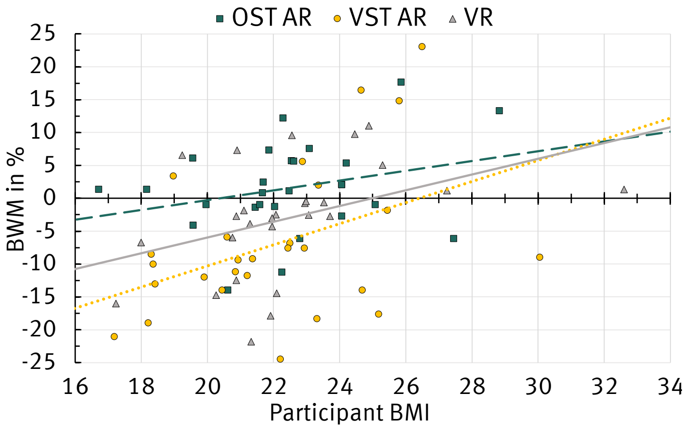

Figure C4.6: The chart shows body weight misestimations (BWM) in relation to the participants' BMI per condition.

Body Weight Estimation

Confirming hypothesis H3, body weight estimations differed significantly between the OST AR condition and the VST AR condition, $t(78) = 3.38, p = 0.001, d = 0.90$ or the VR condition, $t(78) = 1.86, p = 0.005, d = 0.59$. Results are depicted in Figure C4.6.

The further exploratory investigation of the impact of our conditions on the relation between the participant's BMI and the body weight estimation revealed a significant regression equation, $F(5, 75) = 5.40, p < .001$, with an adjusted R^2 of .22. The prediction followed the equation BWM $= 1.47 + 0.74 \cdot$ Participant BMI $- 8.03 \cdot$ Condition A $- 4.65 \cdot$ Condition B$+ 0.86 \cdot$(Participant BMI$\cdot$Condition A)$+ 0.45 \cdot$(Participant BMI$\cdot$Condition B) where Condition A was OST AR = 0, VST AR = 1, VR = 0 and Condition B was OST AR = 0, VST AR = 0, VR = 1. The regression did neither reveal a significant impact of the participants' BMI on body weight estimations in the OST AR condition $t(75) = 1.14, p = .255$, nor did it reveal a significant interaction between OST AR condition and VST AR condition, $t(75) = 1.01, p = .317$, or OST AR condition and VR condition, $t(75) = 0.52, p = .603$.

4.5.2 Qualitative Feedback

The interviews have been evaluated using a *Miro* board (Miro, 2021) and following thematic analysis (Braun & Clarke, 2006). All answers were clustered on sticky notes within the context of their question.

During our analysis, the initial deductive mapping of the answers was broken up, and the answers were inductively re-clustered into feedback on the perception of the holographic mirror itself and the perception of the avatar.

Perception of the Holographic Mirror

Setting up the equipment for the holographic mirror was judged as quick and easy by most participants ($n = 23$). 13 participants perceived the holographic mirror as part of the physical room (e.g., it seemed like the mirror was attached to the wall or they recognized the reflection of the virtual background). Seven participants criticized the virtual mirror, including its transparency, the image quality, and the computer-animated reflection. Two participants found it disturbing that they could still see the real world.

The limited FOV of the HoloLens 2 was noticed by a majority of participants ($n = 20$). 17 participants mentioned the narrow vertical FOV and six the narrow horizontal FOV. Four of them reported that not only the mirror but also the avatar was cut off at the legs. However, the narrow FOV was negligible for 14 participants, as everything relevant could still be observed.

None of the participants stated that the limited FOV prevented them from performing tasks. The majority of the participants described the holographic mirror as not particularly bright in contrast to the environment ($n = 24$).

Perception of the Avatar

The avatar's general appearance was noticed positively by seven participants, as it appeared human and had a suitable body size or skin/hair color. Seven participants criticized the appearance because of wrong skin/hair color, clothing, or body proportions. The face was criticized in particular (no facial expression, fixed eyes, impersonal).

The general pose and movements of the avatar were positively evaluated, stating that the own movements were well mirrored ($n = 7$). Eight participants judged the movements to lack quality (robotic movements, bent hip, not accurately executed movements). Faulty or unnaturally bent elbows of the avatar seem to be the most problematic area, presumably due to different arm proportions between the generic avatar and the participants ($n = 9$). Other problematic areas of the avatar were the shoulders ($n = 6$), twisted arms ($n = 3$), the pose of the legs (left knee turned inwards or knock-knees) ($n = 7$), and the pose of the feet, which also were perceived as turned inwards ($n = 4$). In addition, three participants reported having perceived a trembling and a slight latency in relation to the real movement of the legs. Twelve participants perceived the movement of the hands as soft and precise, four perceived them as "choppy" or "robotic", and two perceived time-delayed movement, especially when the hands were not in the direct FOV. Overall, 17 participants noticed that their fingers did not move, and 22 described a wrong hand rotation (due to the mentioned missing degree of freedom). Five participants noted that finger movements would generally contribute to a realistic avatar appearance (“It is a mirror, all movements should be reflected there”).

4.6 Discussion

Our work’s goal was to design and develop a holographic OST AR mirror system, allowing users to interact with the real world during full-body illusion experiences and to evaluate the system with regard to presence and embodiment as well as body weight perception. Additionally, we compared our evaluation’s results to the results of similar and comparable VST AR and VR systems from previous work (Wolf et al., 2020). As expected, participants using our OST AR felt a significantly lower presence compared to VST AR and VR. However, for VBO and agency, we did not find clear differences between the systems. For body weight estimations, we could observe significant differences between OST AR and VST AR, but only descriptive differences between OST AR and VR. We further received extensive qualitative feedback supplementing the quantitative measurements and containing valuable information for further improvements.

4.6.1 Presence

We hypothesized that participants using OST AR would report a lower feeling of presence than participants using VST AR or VR (H1). The expectations could be confirmed for the relevant dimensions general presence, spatial presence, and realism. Hence, our hypothesis H1 could be confirmed. Our results are in line with previous work (Chicchi Giglioli et al., 2019; Cummings & Bailenson, 2016; Waltemate et al., 2018) and confirm our prior assumptions. The presumed reason for the differences could be the systems’ different degrees of immersion, clearly affecting general and spatial presence. Interviews tend to confirm this assumption. For example, most participants immediately noticed the HoloLens 2’s narrow field of view. Interestingly, the partial transparency of the virtual objects was reported as negative by only one participant.

Another factor influencing presence might be the perceived coherence and plausibility of the experience (Latoschik & Wienrich, 2022) as reflected by the realism score. For example, a rendered avatar as a mirror image within the real environment might be not be perceived as plausible as a rendered avatar as a mirror image within a rendered virtual environment. The discrepancy between reality and virtuality was also evident in the interviews, as the avatar's appearance was perceived as incongruous to the environment, particularly when seeing the real body next to the virtual body. Compared to the real environment, the virtual mirror was described as highly salient because of its transparency, image quality, and computer-animated reflection. Although we observed a significantly lower presence compared to more immersive systems, the question arises whether this difference is of relevance or negligible in behavior change scenarios. However, these questions need to be answered by dedicated studies.

4.6.2 Embodiment

For embodiment, we hypothesized that participants using OST AR would report a lower feeling of VBO (H2.1) and agency (H2.2) towards their avatar than participants using VST AR or VR. We could not confirm our hypothesis for VBO (H2.1), since we only found significant differences between VR OST and VR in the VEQ scores. These are generally unexpected but interesting results. The continuous visual observation opportunity of the real body in the egocentric perspective, as already discussed by other researchers (Genay et al., 2021; Wolf et al., 2020), was expected to lower VBO to a greater extent as observed and to lead to more significant differences. Similar to presence, place illusion and the plausibility of the virtual mirror image (Latoschik & Wienrich, 2022) could have also played a more important role. At the same time, research on full-body illusions in AR is still sparse, contributing to the difficulty in hypothesis formulation and allowing for unexpected findings. The qualitative statements support the quantitative results, as no particular display technology-related reason could be identified that clearly hinders VBO. In the context of our work, this result can be interpreted rather positively since the advantages of AR mentioned above might be utilized without a major loss of VBO. However, further research needs to consolidate our findings, especially when fully personalized or less realistic avatars are used.

Contrary to our hypothesis for agency (H2.2), we only found significant differences between OST AR and VR in the one-item question with tendencies for differences between OST AR and VST AR. Initially, we expected that the participants' direct view on the real body in our OST AR system would impact even more negatively on agency (Genay et al., 2021). Compared to VST AR, where the real environment can only be experienced delayed via video stream, or VR, where the entire scene is rendered delayed, the full motion-to-photon latency in OST AR can also be experienced visually and not only proprioceptively. Supporting this assumption, the results of the qualitative data show that delays and inaccuracies in the avatar's movements were particularly noticeable at the arms and legs. Therefore, it is really surprising that the overall differences in agency have not been stronger, suggesting that agency in

AR mirror systems might be more robust than expected. It also indicates that the measured latency of our system, averaging slightly above the threshold where agency might become affected (Waltemate et al., 2016), had a rather small impact. Similar has already been observed by Latoschik et al. (2016) for their screen-based AR mirror system. Considering our evaluation's descriptive results and our post-hoc power analysis, we surely can not finally rule out an influence of the used display technology on both embodiment dimensions. Further research needs to confirm our findings.

4.6.3 Body Weight Estimation

We hypothesized that participants using OST AR would estimate the avatar's body weight differently than participants using VST AR or VR (H3). We could confirm this hypothesis since participants using OST AR estimated the avatar's body weight in comparison to VST AR and VR significantly higher. This is a particularly interesting finding, as it provides the first empirical indications that the display technology, depending on the display properties itself, impact on body weight perception as previously assumed (Wolf et al., 2020). It urges caution when concluding on absolute misestimations of body weight during self-assessment tasks supported by immersive systems, especially when testing user groups with a potentially disturbed body image. For example, underestimating the body weight of a highly personalized avatar as an obese user could be misinterpreted as a misperception caused by a disturbed body image, although the system itself promotes this underestimation. Before interpreting body weight estimations of a single person, a validation of the system's accuracy as a quality criterion based on a large sample seems inevitable. By predetermining system-specific deviation parameters, the absolute misestimations of individuals could be better interpreted.

Further exploration raises additional questions regarding the impact of the display technology on body weight estimations and the interplay with other factors. Although we employed a full-body illusion in a similar quality as Wolf et al. (2020), we could not confirm the previous observations where a significant influence of participants' BMI on body weight estimates was shown. While this effect has priorly been observed as a result of employing avatar embodiment (Wolf et al., 2021) or avatar personalization (Thaler et al., 2018a), it is really interesting to observe that the predictive influence of BMI on body weight estimations decreases in our case with the different used display technology. This could point to another underlying mediator influenced by a general altered avatar perception due to system technology. However, further research is required to evaluate this observation systematically.

4.6.4 Implications

With regard to user experience and future use of AR full-body illusions in mental health, we showed that participants using our holographic AR mirror perceived similar high feelings of embodiment as participants using a high-immersive VR mirror system (Wolf et al., 2020) similar to those used for mental health supporting applications (Matamala-Gomez et al., 2021; Turbyne et al., 2021). For presence, we measured lower feelings as usually observed for VR mirror systems (Waltemate et al., 2018; Wolf et al., 2020). However, the relevance of the observed level of presence in our OST AR system is very difficult to assess without having conducted a controlled comparative study on efficacy since literature in this direction seems sparse (Genay et al., 2021).

More important seems to be the observed differences in body weight estimations between our OST AR systems and the systems used for comparison. The observed deviations, especially between the two AR systems, were enormous. For example, an avatar with an original weight of 68 kg would on average be estimated to weigh 63.29 kg in VST AR and 69.07 kg in OST AR. This example shows that an absolute interpretation of the weight estimate might be meaningless without a prior determination of the systemic bias. However, before this bias can be accurately determined, further research is needed on the underlying factors that influence the overall perception of the avatar and, in particular, body weight in immersive environments. This conclusion does not mean that a drastically weight-modified avatar could not be used in both systems as an adequate stimulus for behavioral change with the help of the Proteus effect. Consequently, the strength of the induced effect might differ for the same stimulus depending on the display technology and its bias.

Besides the noticed and discussed difference in presence and body weight estimations, our system offers users the opportunity to remain in the real environment while still having the possibility to confront themselves with a realistically appearing modified self-replica. Hence, direct comparisons between the virtual and the real body seem feasible without a heavy loss in the feeling of embodiment. Furthermore, an interaction between users and non-immersed people during exposition seems possible. A final potential advantage to be mentioned is the ease of use of our AR mirror system. With the technologies used, the users only have to put on the HoloLens 2 without having to attach additional markers or picking up controllers, being directly able to observe their mirror image.

4.6.5 Limitation and Future Work

In addition to the limitations already discussed and to the directions for further work already mentioned, we would like to add a few more points. First, in our evaluation, we did not collect comparative data but relied on data from previous work. When interpreting the results of our statistical analyses, it should be noted that although we tried to create the most comparable circumstances, there were still differences between our OST AR system and the VR and VST AR systems (e.g., markerless tracking vs. tracker-based tracking, different environments). For this reason, a holistic comparison under controlled conditions within the same time period is essential to confirm our findings.

Second, our work showed partially significant differences in body weight perception between the previously collected VST AR and VR conditions and our developed OST AR condition. The used OST display differed by its nature in many aspects from the previously used displays (e.g. FOV, resolution, luminosity). These properties have also led to significant differences in presence. Future research is needed to systematically investigate which displays' exact properties cause the observed differences in perception and how relevant they are for different use cases. When comparing presence between AR and VR, the use of questionnaires tailored to cross-media comparisons, such as the ITC-SOPI (Lessiter et al., 2001), should be considered.

Third, we investigated the feasibility of AR full-body illusions and evaluated their user experience in terms of potentially relevant treatment effect mediators. However, although our work was motivated toward mental health, finding the optimal setup for therapeutic use was not our intention. Therefore, future work needs to embed our results in an appropriate therapeutic setting. With rapidly advancing technology, the use of personalized and modifiable avatars might also be considered (Bartl et al., 2021b; Döllinger et al., 2019; Thaler et al., 2018a).

4.7 Contribution and Conclusion

Our presented novel holographic AR mirror expands the range of full-body illusion systems for behavior modification in the broad context of the Proteus effect towards OST display technology, which has so far been sparsely used. Our work further provided initial comparative insights between OST AR, VST AR, and VR embodiment mirror systems, revealing differences in presence and body weight perception that need to be further explored for a final classification in the given context. Interestingly, the AR mirror conveyed a similar feeling of embodiment as the more immersive solutions.

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Author Contributions

Erik Wolf conceptualized large parts of the experimental design, developed large parts of the Unity application, including the avatar animation system, collected two-thirds of the data, and took the lead in writing the manuscript. Marie Fiedler supported the conceptualization of the experimental design, adapted the Unity application for the experiment, collected one-third of the data, and performed most of the data analysis. Nina Döllinger supported the data analysis. Marie Fiedler and Nina Döllinger supported the data analysis. Carolin Wienrich and Marc Erich Latoschik conceived the original project idea, discussed the study design, and supervised the project. All authors continuously provided constructive feedback and helped to shape the study and the corresponding manuscript.

Supplementary Material

Qualitative Interview Questions

General questions about the experience:

1. How elaborate did you find the setup of the system?
2. How much did you perceive the virtual mirror as belonging to the room? What contributed to it? What was distracting?

Questions about the luminosity:

1. Did you perceive the virtual mirror as glowing or otherwise standing out from the real environment?

Questions about the field of view:

1. Did you have trouble keeping the entire mirror in view?
2. If the question was answered "yes":
    a) When and how often did this occur?
    b) How did you go about viewing the entire mirror?
    c) How exhausting did you find it to not be able to see the entire mirror?
    d) Did this prevent you from completing the tasks?

Questions about the avatar perception:

1. How real did you perceive the avatar to be?
2. What contributed to it? What was distracting?
3. Did you notice any other annoying points about the avatar?

Questions about the avatar trembling:

1. How "stable" did the avatar's pose seem to you? (free from trembling and other disturbances)

Questions about the pose accuracy:

1. Did you notice a time delay in the avatar's movements? If so, did it affect specific body parts?
2. How accurate to your real pose was the avatar's pose?

Questions about the avatar hands and fingers:

1. How smoothly did you perceive the movement of the avatar's hands in the mirror?
2. How realistic did you feel the pose of the virtual hands?
3. How accurate did you perceive the rotation and tilt of the virtual hands in relation to your own?
4. Did you perceive that the fingers did not move? If so, did that bother you?

Chapter 5

Plausibility and Perception of Personalized Virtual Humans between Virtual and Augmented Reality

This chapter has been published as follows:[1]

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Figure C5.1: The figure shows a virtual human within each of our three realized conditions. The left image shows the VR condition, the middle one the video see-through AR condition, both taken from Varjo XR-3 HMD screen view. The right image shows a composition of the optical see-through AR condition, originally realized by a Microsoft HoloLens 2 and captured by a DSLR camera.

[1] As part of the dissertation, the published text was editorially revised, with only slight orthographic, stylistic, and formal adjustments, while completely retaining the original semantics.

Abstract

This article investigates the effects of different XR displays on the perception and plausibility of personalized virtual humans. We compared immersive virtual reality (VR), video see-through augmented reality (VST AR), and optical see-through AR (OST AR). The personalized virtual alter egos were generated by state-of-the-art photogrammetry methods. 42 participants were repeatedly exposed to animated versions of their 3D-reconstructed virtual alter egos in each of the three XR display conditions. The reconstructed virtual alter egos were additionally modified in body weight for each repetition. We show that the display types lead to different degrees of incongruence between the renderings of the virtual humans and the presentation of the respective environmental backgrounds, leading to significant effects of perceived mismatches as part of a plausibility measurement. The device-related effects were further partly confirmed by subjective misestimations of the modified body weight and the measured spatial presence. Here, the exceedingly incongruent OST AR condition leads to the significantly highest weight misestimations as well as to the lowest perceived spatial presence. However, similar effects could not be confirmed for the affective appraisal (i.e., humanness, eeriness, or attractiveness) of virtual humans, giving rise to the assumption that these factors might be unrelated to each other.

Keywords

Mixed reality, immersion, coherence, presence, body weight perception, body image, serious application, uncanny valley

5.1 Introduction

Virtual representations of human beings, often called virtual humans, virtual alter egos (when user-personalized), or avatars (when user-controlled) (Bailenson & Blascovich, 2004), are integral to various mixed, augmented, and virtual reality applications (MR, AR, VR – XR for short). Examples can be found in various domains like mental health (Matamala-Gomez et al., 2021; O'Connor, 2019), entertainment (Lugrin et al., 2018; Valve, 2020a), and education (Lugrin et al., 2016; Scavarelli et al., 2021). In the area of mental health, the application of virtual humans for working on body perception in directions like body weight management or body image intervention is particularly promising (Döllinger et al., 2019, 2022c; Horne et al., 2020; Turbyne et al., 2021). In this regard, an accurate and plausible representation and perception of a virtual human is beneficial (Wienrich et al., 2021a). Recent work has explored the use of personalized, photorealistic virtual alter egos for this purpose with great success

(Döllinger et al., 2022c; Thaler et al., 2018a; Waltemate et al., 2018). However, not only the virtual human or virtual alter ego itself but also the mediating display technology and the resulting XR experience can influence the perception of a virtual human. For example, Wolf et al. (2022b) recently compared the perception of embodied but non-personalized avatars between VR, video see-through AR (VST AR), and optical see-through AR (OST AR) and revealed significant perceptual differences in body weight estimations. It is a crucial finding since already a wide variety of display systems (e.g., various VR or AR see-through HMDs, AR projectors, or CAVE-like systems) are used in the research of body perception (Wolf et al., 2020), and as consumer technology advances rapidly, the heterogeneity is expected to rise. While research on the perception between different types of virtual humans themselves (Bartl et al., 2021b; Hepperle et al., 2022; Lugrin et al., 2015; Mori et al., 2012) or between desktop and VR applications (Hepperle et al., 2020, 2022; Herrera et al., 2018; D. Roth & Wienrich, 2018) have been studied intensively, investigations between different XR display systems seem rather scarce and require more attention (Wolf et al., 2020).

To address this gap, our work explores the plausibility and perception of virtual alter egos between different XR display systems. In our experiment, 42 participants observed their animated, personalized, photorealistic virtual alter ego in a controlled environment using (1) a VR system, (2) a VST AR system, and (3) an OST AR system (see Figure C5.1). For elaborating on the display-specific perceptual differences recently discovered by Wolf et al. (2022b), the body weight of the virtual alter ego was repeatedly changed while the participants had to estimate it. After XR exposure, participants judged the spatial presence felt during the XR experience and rated the virtual alter ego's appearance on further body perception-related measures (i.e., virtual human plausibility and affective appraisal). In the following, we define the characteristics of our display device-specific XR experiences based on recently introduced novel theoretical models (Latoschik & Wienrich, 2022; Skarbez et al., 2021b; Wienrich et al., 2021b) and compare the results of our measures between the experiences. We further explore the modification and estimation of virtual humans' body weight as a method for determining display-related differences in virtual human perception. Hence, our work contributes first empirical data to the verification of the theories, applies them to the important application field of virtual human perception, and provides further understanding of different XR experiences differ from each other.

5.2 Related Work

5.2.1 Spatial Presence and Virtual Human Plausibility

Skarbez et al. (2021b) recently introduced a revised version of Milgram's reality-virtuality continuum (Milgram et al., 1995) as a taxonomy for describing XR experiences. While the initial version of Milgram related mainly to the used visual display, the revised version extends the continuum to all external senses and consists of the dimensions (1) immersion, (2) coherence, and (3) extent of world knowledge.

(1) *Immersion*, or rather system immersion as defined by Slater (2009), is determined by a system's objective hardware device specifications. The user's subjective reaction to a display's degree of immersion is the feeling of spatial presence (or place illusion, Skarbez et al., 2021b). In other words, the higher the immersion of a display, the more the user feels really being in a virtual environment (Slater, 2009). Table C5.1 summarizes the specifications of our used devices.

Specification	Varjo XR-3	HoloLens 2
Horizontal FoV	115°	43°
Vertical FoV	80°	29°
Foveal Res.	1920 × 1920 px, 70 PPD	1440 × 936 px, 30 PPD
Peripheral Res.	2880 × 2720 px, 30 PPD	1440 × 936 px, 30 PPD
Refresh Rate	90 Hz	60 Hz
Luminosity	High	Low
Transparency	No	Yes

Table C5.1: The table compares the specifications of our HMDs used. The Varjo XR-3 contains a separate display for the foveal area ($27° \times 27°$).

(2) *Coherence* refers to the conformity of different sensory information a user perceives during an XR experience. An example of our displays is the realism coherence of the content, which differs significantly between VR (rendered content and rendered environment) and AR (rendered content and real environment, Skarbez et al., 2021b). The user's subjective judgment of coherence leads to the feeling of plausibility of the XR experience (or plausibility illusion, Skarbez et al., 2017, 2021b).

(3) *Extent of world knowledge* describes the degree of reality a system incorporates (e.g., by remodeled environments or see-through functionality) into an XR experience (Milgram et al., 1995). The user's subjective reaction to world knowledge could be described as the user's real-world awareness (Skarbez et al., 2021b). Since our work focuses on immersion

and congruence, we consider Skarbez et al. (2021a) to control important environmental cues influencing the world knowledge (e.g., constant room-scale, physically plausible objects, similar lighting).

An alternative theoretical model by Latoschik and Wienrich (2022) extends the first two dimensions of Skarbez et al. (2021b). It similarly centers on *congruence* but argues that all congruence activations between cognitive, perceptual, and sensory layers (e.g., expectations, experiences, and habits) contribute to the plausibility of an XR experience reflected in various XR-related qualia, such as spatial presence. Therefore, device specification differences, like a larger field of view (FoV) or a higher resolution, lead to a stronger device-specific sensory congruence, while higher content transparency of virtual objects would cause incongruence. The device-specific congruencies impact the plausible generation of spatial cues and ultimately the XR qualia spatial presence. Mal et al. (2022) further elaborated on the plausibility of virtual humans and highlighted (1) the virtual human's appearance and behavior congruence, which defines whether a virtual human appears and behaves plausibly within the environment, and (2) the virtual human's congruence with the virtual environment, which defines whether the virtual human's appearance and behavior are plausible in relation to the environment, as two factors to consider.

For our study, we realized the VR and VST AR conditions by a Varjo XR-3 (Varjo, 2021b), while we used a HoloLens 2 (Microsoft, 2019a) for OST AR (see Table C5.1). In all immersion-related properties except peripheral resolution, the XR-3 can be considered to provide a higher device-specific congruence, which leads in both introduced models to a higher spatial presence. For the virtual human plausibility, we argue that the differences between VR and AR are more crucial and expect that, for example, a more congruent rendering of the content will lead to a higher virtual human plausibility. With regard to the practical relevance of the presented models, Wienrich et al. (2021b) also recently highlighted spatial presence and plausibility as two major dimensions for quantifying the overall quality of an XR experience. For the practical application of XR in the areas like mental health, a high overall quality of an XR experience has been introduced as a necessary hygiene factor for achieving desired effects (Wienrich et al., 2021a). Therefore, we consider spatial presence and plausibility as important factors for our work and formulate the following research question.

Research Question

RQ1: How do differently immersive and congruent displays affect spatial presence and virtual human plausibility?

5.2.2 Virtual Human Perception

We examine the influence of different immersive and congruent displays on the virtual human perception-related measures of body weight perception and affective appraisal. Following the introduced theoretic model of Latoschik and Wienrich (2022), the participants' cognitive and perceptual experiences regarding a virtual human can influence the interpretation of its plausibility and its perception. Hence, the kind of virtual human presentation is crucial when measuring virtual human perception. For example, the presentation of a generic virtual human could lead to a subjective interpretation regarding its generic appearance. To avoid participants' subjective interpretations and to achieve better comparability between display conditions, it suggests using personalized virtual humans as stimuli.

In addition, the observation perspective on a virtual human can affect its perception. For example, Neyret et al. (2020a) compared the impact of the perspective on virtual human perception and emphasized the importance of a third-person presentation for a more unbiased judgment. This includes the embodiment, which involves a change of observational perspective of a virtual human and implicitly manipulates its assessment. Recent work showed, for example, that the embodiment of a generic virtual human can lead to an altered body weight perception (Wolf et al., 2021) or recognition of body weight changes (M. Jung et al., 2020). Using embodied avatars could further lead to an uncontrolled exposition with the avatar, as the observation perspective on the body changes according to the participants' movements, leading to highly individual impressions. Here, prior work has clearly highlighted the importance of providing a holistic picture of the body in body perception research (P. L. Cornelissen et al., 2018; Thaler et al., 2019). Hence, to keep the presentation of virtual humans as stable as possible, it suggests presenting them from a third-person perspective without embodiment as various prior works did (Horne et al., 2020; Piryankova et al., 2014a; Thaler et al., 2018a, 2018b, 2019). Through the use of non-embodied virtual alter egos, we expect to decrease interindividual differences in body weight perception by providing all participants a controlled reference template for their judgments (K. K. Cornelissen et al., 2016).

Body Weight Perception

Applications in the area of mental health like body image interventions can benefit greatly from the use of virtual humans in XR (Döllinger et al., 2022c; Horne et al., 2020; Turbyne et al., 2021). They also show huge potential in the research of body perception (Thaler, 2019). We further suggest that body weight estimates can also serve as a measure for evaluating display-specific perceptual differences. Wolf et al. (2020) recently summarized that systems used in body weight perception-related works differed widely in their implementation, including the display type and the conveyed XR experience and raised the question of whether a system's implementation might influence results of investigations and their interpretation. Indeed, prior work compared body perception of a photorealistic but generic embodied virtual human between a VR, a VST AR, and an OST AR display and found highly significant differences of up to 8.5 % in body weight estimations between the display conditions (Wolf et al., 2022b). What appears to be a disadvantage in the practical application of XR in the area of mental health, namely system-related differences, may prove to be advantageous when investigating the effects of different display types on the perception of virtual humans. Therefore, we are investigating the use of body weight estimates in this direction and formulating the following research question for our work.

Research Question

RQ2: How do differently immersive and congruent displays affect the perception of a virtual alter ego's body weight?

Affective Appraisal

Another part of the virtual human perception to be considered is their affective appraisal, especially regarding the so-called uncanny valley effect (Mori, 1970). The effect describes the paradoxical reaction that the perception of a virtual human changes from pleasantness to eeriness as soon as the virtual human's appearance approaches but does not fully reach a convincing human-like appearance (Mori et al., 2012). The feeling of uncanniness towards a virtual person is thereby determined by its human likeness and the affinity towards its observer. Since our and similar work (Döllinger et al., 2022c) implements photorealistic and personalized virtual alter egos, which should be fairly close to a human-like appearance, the question arises whether the differences between our XR experiences and their presumed effects on the congruence of the virtual alter ego could also influence its affective appraisal. While there has been a great deal of research on different types of virtual humans, e.g., depending on their anthropomorphism (Chaminade et al., 2007; Lugrin et al., 2015), reconstruction method (Bartl et al., 2021b), stylism (Hepperle et al., 2020, 2022), and many more, presented by the same display type, there seems to be far less research on effects triggered by differently immersive displays and incongruent presentations. In a work comparing the perception of virtual humans between desktop and VR, D. Roth and Wienrich (2018) could not find differences in the uncanny valley relevant measures of humanness, attractiveness, and eeriness (Ho & MacDorman, 2017). Hepperle et al. (2020) found that an uncanny valley effect is more likely to appear in VR than on a desktop screen by employing a similar comparison. However, they could only find greater differences for virtual humans judged to be within the uncanny valley. To our knowledge, there is no work comparing the affective appraisal of virtual humans regarding the uncanny valley between a VR, an VST AR, and an OST AR display. Hence, we are formulating the following research question.

Research Question

RQ3: How do differently immersive and congruent displays affect the affective appraisal of a virtual alter ego?

5.3 Method

A detailed ethics proposal following the Declaration of Helsinki was submitted to the ethics committee of the Institute Human-Computer-Media (MCM) of the University of Würzburg and found to be ethically unobjectionable. During the acquisition and evaluation process of the study, freely available support offers from the Anorexia Nervosa and Associated Disorders organization (ANAD) were explicitly highlighted in case participants would feel uncomfortable regarding their body weight after the study.

5.3.1 Participants

A total of 42 participants (23 female, 19 male) were recruited from the university's participant management system and either received 15 € or student credit points equal to the participation time. Individuals could not register if they (1) had no normal or corrected to normal vision and hearing, (2) had less than ten years of experience with the German language, (3) currently suffered from a diagnosed mental, psychosomatic, or body weight disorder, or (4) had a known sensitivity to simulator sickness. Additionally, one participant had to be excluded after participation due to technical problems during the experiment. 31 participants were students of the local university. Eight of the participants had less than one hour of XR experience, 32 used XR for one to twenty hours, and two used XR already for more than twenty hours. More descriptive data can be found in Table C5.2.

5.3.2 Experimental Task

The participants' experimental task was to observe their previously generated personalized virtual alter ego moving in the virtual environment while sitting in a fixed position within the laboratory. The observation phase consisted of nine cycles in which participants had to judge

Measure	Range	M (SD)
Age	19 – 64	26.21 (10.03)
Body height (m)	1.56 – 1.91	1.73 (0.09)
Body weight (kg)	45.1 – 123.8	71.64 (18.28)
BMI	16.56 – 35.79	23.81 (3.42)

Table C5.2: The table shows age and body measurements of our sample.

the virtual alter ego concerning our measures explained below. In each observation cycle, the virtual alter ego walked with a different (modified) body weight about 1.2 m into the room, posed from the front and both sides, and left the room again. Body weight modifications ranged ± 20 %, split into ± 5 % intervals, and were performed in a counterbalanced manner. In total, the virtual alter ego was visible for 32 s per cycle and provided a holistic picture of itself during this time, as suggested by prior work (P. L. Cornelissen et al., 2018; Döllinger et al., 2022c; Thaler et al., 2019).

5.3.3 Design

Our study followed a 3×1 within-subjects design with *display type* being the independent variable. Hence, each participant performed the experimental task using the *VR*, *VST AR*, and *OST AR* display. The order was counterbalanced. As dependent variables, we captured the participants' feeling of *spatial presence*, perceived *virtual human plausibility*, *body weight perception*, and *affective appraisal*. On an exploratory basis and without prior hypotheses, we investigated the influence of the performed body weight modifications and the participants' gender on body weight perception. Additionally, we monitored simulator sickness-related symptoms before and after exposure. The operationalization of the variables will be explained below.

5.3.4 Measures

Spatial Presence We used the *ITC-Sense of Presence Inventory* (ITC-SOPI, Lessiter et al., 2001) to test whether and to what extent our manipulation of the display type affected participants' feeling for spatial presence. The questionnaire was developed to capture differences cross-media and consists of four presence-related sub-dimensions, from which we only took spatial presence (SP). The averaged scores were taken from 19 items and range from 1 to 5 (*5 = highest SP*).

Virtual Human Plausibility We assessed the presented virtual alter egos' plausibility using the *Virtual Human Plausibility Questionnaire* (VHPQ, Mal et al., 2022). It captures (1) the virtual humans' appearance and behavior plausibility (ABP) and (2) the virtual humans' match to the virtual environment (MVE) using 11 different items, which are all rated on a scale from 1 to 7 (*7 = highest plausibility*).

Affective Appraisal We measured the participants' affective appraisal of the virtual alter ego using the revised version of the *Uncanny Valley Index* (UVI, Ho & MacDorman, 2017). It includes the three sub-dimensions of *humanness* (H), *eeriness* (E), and *attractiveness* (A). The scales examine anthropomorphic properties of the virtual alter ego and range from 1 to 7 (*7 = highest H, E, A*).

Body Weight Perception Our body weight estimations followed the idea of prior work (Döllinger et al., 2022c; Wolf et al., 2020, 2021, 2022b) and served as the operationalization of participants' perception of the virtual alter egos' body weight. Participants had to numerically estimate the presented virtual alter ego's body weight in kg in each observation cycle. We used the estimations to calculate the misestimation M for each body weight modification as $M = \frac{e-p}{p}$, where e is the estimated body weight, and p is the presented body weight. A negative value states an underestimation of the body weight and a positive value an overestimation. Based on the misestimations M, we calculated the average body weight misestimation (BWM) $\overline{M} = \frac{1}{n}\sum_{k=1}^{n} M_k$ over all observation cycles n. As an indicator of the difficulty and uncertainty of participants' individual body weight estimations, we further calculated the average percentage of absolute misestimation as $\overline{A} = \frac{1}{n}\sum_{k=1}^{n} |M_k|$.

Simulator Sickness

To control whether our used displays systematically provoked simulator sickness (e.g., by latency of the VST cameras or general latency jitter, Stauffert et al., 2018, 2020), we captured whether and to what extent participants experienced simulator sickness-associated symptoms. Participants assessed the 16 items of the *Simulator Sickness Questionnaire* (SSQ, Bimberg et al., 2020; Kennedy et al., 1993) before performing the first condition of the study and after the last one. The total score of the questionnaire ranges from 0 to 235.62 (*236 = strongest simulator sickness*). An increase in the score by 20 between a pre- and post-measurement indicates the occurrence of simulator sickness (Stanney et al., 1997).

5.3.5 Apparatus

Hard- and Software

The virtual environment was implemented using *Unity* 2020.3.11f1 LTS (Unity Technologies, 2020). It ran on a powerful workstation that consisted of an *Intel Core i7-9700K CPU*, a *NVIDIA GeForce RTX 2080 Ti*, and *32 GB RAM*. We further provided participants with an ordinary office workstation equipped with keyboard, mouse, and 24-inch LCD screen, which they used to answer questionnaires outside of XR presented using LimeSurvey 4 (LimeSurvey GmbH, 2020).

VR and VST AR Our study's VR and VST AR conditions were realized using a *Varjo XR-3 HMD* (Varjo, 2021b). The technical specification of the display can be found in Table C5.1, left. The absolute position of the HMD was tracked by four *SteamVR Base Stations 2.0*. In the VST AR display mode, the real environment was captured by two 12 Mpx VST low latency cameras running at 90 Hz. According to the manufacturer, the recorded content is displayed on the HMD with a latency of < 20 ms. Since this low latency is achieved by using hardware-accelerated integration on the device directly, we could not verify the latency using trivial latency measurement methods (Stauffert et al., 2020, 2021). To integrate the XR-3 into our application, we used Varjo's Unity XR plugin [2] in conjunction with *Varjo Base*, both in version 3.2.0.

OST AR The OST AR condition of our study was realized using a *Microsoft HoloLens 2* (Microsoft, 2019a). The technical specification of the display can be found in Table C5.1, right. The absolute position was tracked using the built-in inside-out tracking. In our evaluation, the HoloLens 2 was connected via 100 MBit/s ethernet to the previously mentioned high-end PC used to render the content via *Holographic Remoting*. For integrating the HoloLens 2 into our application, we used Microsoft's *Mixed Reality Toolkit (MRTK)* [3] in version 2.7.0.

Environment

To keep the extent of world knowledge on our dependent variables across VR and AR as constant as possible, we aimed for a virtual environment similar to the real environment in the VR condition (Skarbez et al., 2021a). To this end, we created a 3D model of the real-world laboratory in which the experiment was conducted (see Figure C5.1). To ensure that the virtual and real environments were properly aligned, an environmental calibration using

[2] https://github.com/varjocom/VarjoUnityXRPlugin
[3] https://github.com/microsoft/MixedRealityToolkit-Unity

a predefined anchor point in both environments was performed by putting the HMD on this point. In both the virtual and real environment, we left the laboratory door open during the study, allowing the virtual alter ego to leave the room during a weight change to increase the overall plausibility. By masking the room's door in the aligned virtual environment as a pass-through object [4], we could realize that the real door also occluded the virtual alter ego in the AR conditions. Since the experimenter, who was also positioned in the laboratory during the study, could have been observed in the AR conditions, we concealed him and the used PC with two fabric walls. In consequence, participants could only see the static objects of the environment. While the whole virtual environment was rendered in the VR condition, only the virtual alter ego was shown in the AR conditions (see Figure C5.1).

Virtual Alter Ego

Generation To generate the personalized virtual counterpart of the participants, we use the method proposed by Achenbach et al. (2017). A custom-built multi-DSLR-camera setup (see Bartl et al., 2021b, Figure 1, top) produces the input images for a multi-view stereo reconstruction step resulting in a dense point cloud of the scanned subject. Pose and shape parameters of a statistical model of human shape variation are optimized to fit the scanner data. A final non-rigid deformation step ensures a closer match to the scanner data, as the statistical model parameters alone cannot completely explain the observation. The model is based on a fully rigged template mesh from the Autodesk Character Generator (Autodesk, 2014), resulting in a virtual alter ego fully compatible with the common XR engines like Unity.

Animation We imported the generated virtual alter egos into Unity using a custom FBX-based runtime loader. It automatically generates a fully rigged, humanoid virtual character object immediately ready for animation. During our study, the virtual alter egos were animated using Unity's built-in character animation system playing pre-recorded humanoid animations. The animations were recorded using the system of Wolf et al. (2020). By using FinalIK's *Humanoid Baker* [5], the movements were created directly as Unity-compatible animations.

Modification For modifying the body weight of the virtual alter ego at runtime, we follow the method described by Döllinger et al. (2022c). They build a model of human shape variation based on principal component analysis (PCA) by non-rigidly registering a template mesh to a subset of the CAESAR database (Robinette et al., 2002), which consists of

[4]https://developer.varjo.com/docs/unity-xr-sdk/masking-with-varjo-xr-plugin
[5]https://assetstore.unity.com/packages/tools/animation/final-ik-14290

Figure C5.2: The figure shows an exemplary generated virtual alter ego with modified body weight of BMI $= 22$ (left) and BMI $= 32$ (right) on the same pose within our virtual environment.

3D scans with corresponding anthropometric measurements. Learning the correlation between the measurements and the PCA subspace allows expressing the desired change in body weight as a change in the subspace, which can be used to reconstruct a modified mesh for the virtual alter ego. Improving on similar approaches for body weight modification of virtual alter egos (Piryankova et al., 2014a), Döllinger et al. (2022c) additionally keep a small area of the face region fixed to preserve the virtual alter ego's identity better. Figure C5.2 compares an exemplary generated virtual alter ego with a modified body weight.

5.3.6 Hypotheses

Considering the above-presented literature and the concrete implementation of our experimental conditions, we formulate operationalized hypotheses for each of our variables. As detailed in the last paragraph of Section 5.2.1, we expect for spatial presence and avatar plausibility (RQ1) that our VR and VST AR (using the XR-3) conditions have a similar degree of immersion while the OST AR (using the HoloLens 2) provides a lower degree of immersion. We further expect the VR display to provide a more congruent experience than both of our

AR displays. Supported by empirical works comparing the feeling of presence between different XR experiences (Chicchi Giglioli et al., 2019; Cummings & Bailenson, 2016; Waltemate et al., 2018), we propose the following operationalized hypotheses:

Hypotheses

H1.1: Participants will report a higher ITC-SOPI SP score when using the more immersive VR and VST AR displays than when using the less immersive OST AR display.

H1.2: Participants will report no different VHPQ ABP scores when using the VR, VST AR, and OST AR display.

H1.3: Participants will report a higher VHPQ MVE score when using the more congruent display (VR) than when using the less congruent ones (VST AR and OST AR).

As highlighted in Section 5.2.2, we presume for body weight perception (RQ2) an influence of the display used based on previous work (Wolf et al., 2020, 2022b) and formulate the following undirected hypothesis:

Hypothesis

H2.1: Participants' body weight misestimations $\overline{M}$ of the observed virtual alter egos will differ between the used VR, VST AR, and OST AR displays.

Following our argumentation in Section 5.2.2, we formulate for the affective appraisal of the virtual alter egos (RQ3) our hypothesis based on the performed comparisons between desktop and VR systems (Hepperle et al., 2020; D. Roth & Wienrich, 2018) and expect:

Hypotheses

H3.1: Participants will report no different UVI H scores when using the VR, VST AR, and OST AR display.

H3.2: Participants will report no different UVI A scores when using the VR, VST AR, and OST AR display.

H3.3: Participants will report no different UVI E scores when using the VR, VST AR, and OST AR display.

5.3.7 Procedure

Our study followed the procedure visualized in Figure C5.3. It was divided into a body scan and exposure session, which were performed on two different appointments. The time between the two sessions ranged from 10 min to a maximum of seven days. If the sessions were performed on two different days, participants were asked to wear the same clothing for both sessions.

In the body scan session, participants were first informed about the local COVID-19 regulations, received information about the scans process, gave their consent, and generated a personal pseudonymization code to store the captured data. Afterwards, participants answered demographic questions and further questions about their prior VR and AR experiences. Lastly, the experimenter measured the participant's body height and body weight and performed the body scan as explained in Section 5.3.5 without shoes. The whole body scan session took on average 23 min.

In the exposure session, participants first received information about the following exposure, gave their consent, generated a personal pseudonymization code for storing the data collected during the study and answered the pre-SSQ. Afterwards, the exposure phase for each display type followed in a counterbalanced order. The experimenter explained the corresponding HMD, made sure the participants wore it correctly, and started a test sequence that presented all relevant information using pre-recorded audio and text instructions. It further triggered the animations and body weight modifications of the virtual alter ego. Partici-

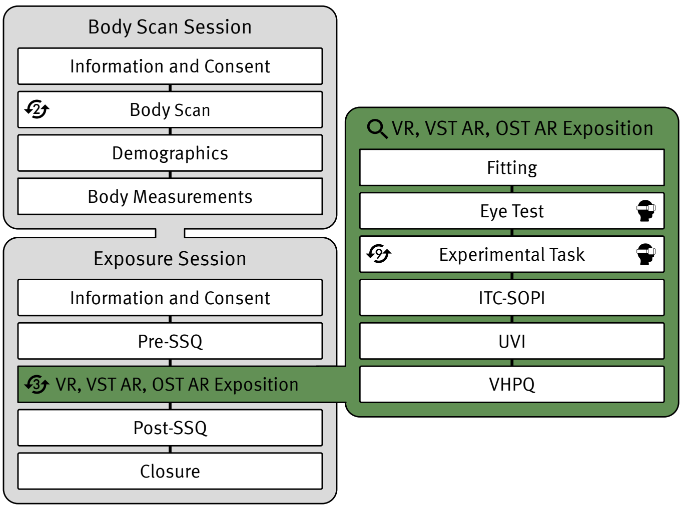

Figure C5.3: The figure shows the experimental procedure of our study.

pants performed the experimental task explained in Section 5.3.2. Hence, they estimated the body weight nine times and answered the ITC-SOPI, UVI, and VHPQ directly afterwards. After finishing all three conditions, the participants answered the post-SSQ and could leave further comments on their body weight estimation strategy and the study itself. The entire exposure session took on average 58 min.

5.4 Results

The statistical analysis of our data was performed using *SPSS* version 27.0.1.0 (IBM, 2020). Before comparing our conditions, we performed tests for normality and sphericity of our dependent variables to check whether the prerequisites for parametric testing were met. While normality and sphericity were given for BWM $\overline{\text{M}}$, the assumption of sphericity was violated for ITC-SOPI SP, UVI H, UVI A, and UVI E. For each of the priorly mentioned variables, we calculated a repeated-measures ANOVA using Greenhouse–Geisser adjustment where necessary to test for differences between our three groups. Due to a violation of normality, we calculated a Friedman-test for each of ITC-SOPI EVN, VHB ABP, and VHB MVE. For all variables discovering significant differences between groups, we decided to calculate separate post-hoc tests. All tests were performed against an α of .05. For directed hypotheses we calculated one-sided tests, for undirected two-sided tests (Field, 2017). The descriptive values and the statistical tests of the comparisons are summarized in Table C5.3. Any calculated post-hoc tests or further exploratory analyses can be found in the corresponding sections of the measurements below. On an exploratory basis, we examined differences between gender and VR experience for all measures and found no significant differences.

5.4.1 Spatial Presence and Plausibility

Confirming hypothesis H1.1, the comparison of ITC-SOPI SP data showed significant differences between our conditions, $F(1.583, 82) = 3.768, p = .038, \eta_p^2 = 0.084$. The performed one-tailed paired-sample post-hoc t-tests revealed significant differences between VR and OST AR, $t(41) = 1.80, p = .040, d_z = 0.28$, and between VST AR and OST AR, $t(41) = 2.66, p = .006, d_z = 0.41$. No significant difference was found in a two-tailed comparison between VR and VST AR, $t(41) = 0.42, p = .676, d_z = 0.06$. All results for spatial presence and plausibility are shown in Figure C5.4.

In line with our hypothesis H1.2, the calculated comparison of the VHPQ ABP data showed no significant differences between our conditions, $\chi^2(2) = 3.768, p = .152, W = 0.045$. Hence, we calculated no post-hoc tests.

Measure	Range	VR	VST AR	OST AR	p
		M (SD)	M (SD)	M (SD)	
Spatial Presence					
ITC-SOPI SP	[1 – 5]	2.58 (0.65)	2.61 (0.64)	2.38 (0.68)	.038 *
Virtual Human Plausibility					
VHPQ ABP	[1 – 7]	5.23 (0.80)	5.13 (0.77)	4.93 (0.87)	.152
VHPQ MVE	[1 – 7]	5.82 (0.78)	5.26 (0.98)	4.81 (1.21)	$<$ .001 **
Body Weight Perception					
BWM $\overline{\text{M}}$		-0.11 (4.86)	-0.20 (6.05)	2.06 (5.08)	$<$ .001 **
Affective Appraisal					
UVI H	[1 – 7]	3.61 (1.17)	3.45 (1.11)	3.35 (1.15)	.091
UVI A	[1 – 7]	4.53 (0.87)	4.49 (0.86)	4.55 (0.89)	.587
UVI E	[1 – 7]	3.61 (0.78)	3.57 (0.82)	3.60 (0.75)	.834

Table C5.3: The table shows the descriptive values together with the p-values for each measurement compared between the different display types. Single-asterisks indicate significant and double-asterisks highly significant p-values.

Confirming hypothesis H1.3, the calculated comparison of the VHPQ MVE data showed significant differences between our conditions, $\chi^2(2) = 21.319, p < .001, W = 0.254$. Pairwise one-tailed post-hoc comparisons using Dunn's test revealed significant differences between VR and VST AR, $z = 2.56, p = .005, r = 0.40$, and between VR and OST AR, $z = 4.15, p < .001, r = 0.64$. No significant difference was found in a two-tailed comparison between VST AR and OST AR, $z = 1.58, p = .114, r = 0.24$.

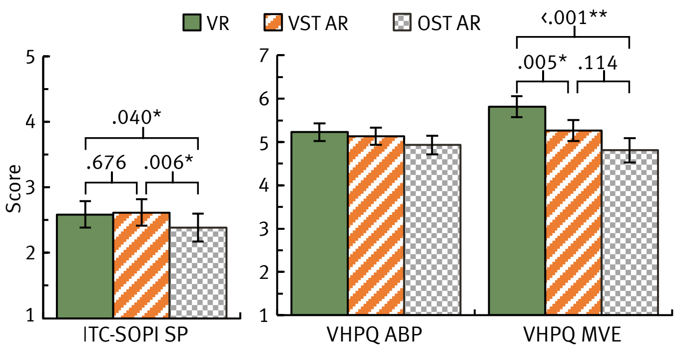

Figure C5.4: The chart shows the ITC-SOPI and the VHPQ scores for each condition. Error bars represent 95 % confidence intervals. Single-asterisks indicate significant and double-asterisks highly significant p-values.

5.4.2 Body Weight Perception

Regarding our hypothesis H2.1, the calculated comparison of the participants' misestimations of their virtual alter ego's body weight ($\overline{M}$) showed significant differences between our conditions, $F(2, 82) = 9.956, p < .001, \eta_p^2 = 0.195$. The calculated two-tailed paired-sample post-hoc t-tests revealed no significant differences between VR and VST AR, $t(41) = 0.17, p = .865, d_z = 0.03$, but between VR and OST AR, $t(41) = 3.63, p < .001, d_z = 0.56$, and between VST AR and OST AR, $t(41) = 3.67, p < .001, d_z = 0.57$. As we found no significant differences between VR and VST AR, we did not accept our hypothesis H2.1. A further calculated post-hoc t-test showed that body weight estimations differed significantly from zero in the OST AR condition, $t(41) = 2.62, p = .012, d = 0.40$.

On an exploratory basis, we further investigated the body weight misestimations $\overline{M}$ with regard to the performed body weight modifications and gender differences. To this end, we added the modification level ($\pm 20\%$ in 5% intervals) as a within-subject factor and gender (female and male) as a between-subject factor to the repeated measures ANOVA calculated for H3.1. Test results showed no significant main effect for the modification level, $F(8, 320) = 1.33, p = .230$ (see Figure C5.5). With regard to gender differences, no significant main effect was found, $F(1, 40) = 0.51, p = .638$. Furthermore, no significant interaction effects were found within the entire model.

In addition, we explored absolute body weight misestimations $\overline{A}$ with regard to the performed body weight modification and gender differences. Following the exploration approach of $\overline{M}$, we calculated a repeated-measures ANOVA with the within-subject factors display type (VR, VST AR, and OST AR) and modification level ($\pm 20\%$ in 5% intervals) and the between-subject factor gender (female and male). Results showed no significant main

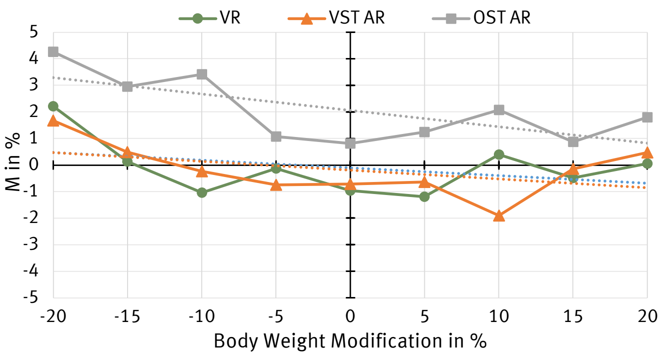

Figure C5.5: The chart shows the body weight misestimations M depending on the performed body weight modification of the virtual alter ego for each condition.

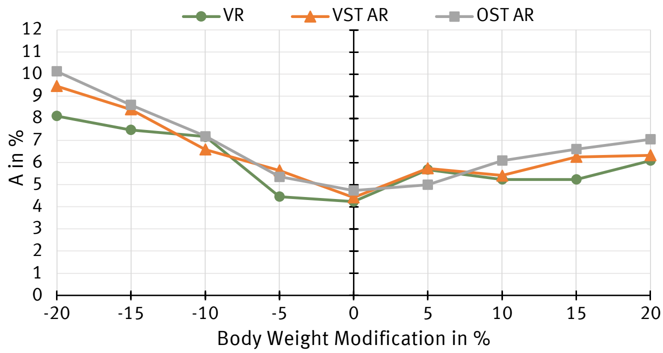

Figure C5.6: The chart shows the absolute body weight misestimations A depending on the performed body weight modification of the virtual alter ego for each condition.

effect for display type, $F(2, 80) = 2.05, p = .135$, but a significant main effect for the modification level, $F(8, 328) = 8.65, p < .001$ (see Figure C5.6). With regard to gender differences, no significant main effect was found, $F(1, 40) = 0.34, p = .562$. Furthermore, no significant interaction effects were found within the entire model.

To further explore the significant differences between modification levels, we averaged the absolute body weight misestimations $\overline{A}$ across the display type and split the modification levels in a high negative modification group ($-10\%, -15\%, -20\%$), a low modification group ($+5\%, 0\%, -5\%$), and a high positive modification group ($+20\%, +15\%, +10\%$). The calculated two-tailed paired-sample post-hoc t-tests revealed significant differences between the high negative modification ($M = 8.13, SD = 4.07$) and the low modification group ($M = 5.02, SD = 2.43$), $t(41) = 5.57, p < .001$, and between the high negative modification and the high positive modification group ($M = 6.03, SD = 3.44$), $t(41) = 2.60, p = .013$, but not between the low modification and the high positive modification group, $t(41) = 1.89, p = .066$.

5.4.3 Affective Appraisal

In line with H2.1, H2.2, and H2.3 on the affective appraisal of the virtual alter egos, we could not find significant differences between VR, VST AR, and OST AR for the virtual alter egos' humanness (H2.1), $F(1.575, 82) = 2.646, p = .091, \eta_p^2 = 0.061$, attractiveness (H2.2), $F(1.540, 82) = 0.452, p = .587, \eta_p^2 = 0.011$, and eeriness (H2.3), $F(1.592, 82) = 0.127, p = .834, \eta_p^2 = 0.003$. Hence, we calculated no post-hoc tests.

5.4.4 Simulator Sickness

To control the influence of our different XR displays on simulator sickness-related symptoms, we compared SSQ pre- and post-measurements (descriptive values in Table C5.2) using a two-tailed Wilcoxon signed-rank test as the normality pre-requirement for parametric testing was violated. The SSQ ratings did differ significantly between pre-measurement ($M = 11.30, SD = 15.85$) and post-measurement ($M = 16.56, SD = 17.27$), $Z = 2.61, p = .009$. However, the observed increase in SSQ scores of 5.26, as well as the absolute post-SSQ score, were below the 20 points indication threshold for the occurrence of simulator sickness (Stanney et al., 1997).

5.5 Discussion

5.5.1 Spatial Presence and Virtual Human Plausibility

Our study presented participants a content-like XR experience using three different displays. While the VR and VST AR experience was realized using a Varjo XR-3, we used a Microsoft HoloLens 2 for the AR OST experience. We assumed that the device with a potentially higher level of immersion (XR-3) would also induce a higher spatial presence (H1.1). Our results fully confirm our assumption since we showed a significantly higher spatial presence for VR and VST VR than for OST AR, but no differences between VR and VST AR. However, when comparing our results to similar prior work, it does not seem to be necessarily the case that the same device provides a similar level of spatial presence in VR and VST AR mode. In Wolf et al. (2020), the researchers used an HTC Vive Pro for both conditions and reported a significantly higher spatial presence for VR than for VST AR. A explanation could be the quality of the video see-through implementation. While the XR-3 uses two high-resolution and low-latency see-through RGB cameras (12 Mpx, 90 Hz), the Vive Pro has a lower resolution and refresh rate (0.3 Mpx, 60 Hz). Hence, the technical implementation of the see-through functionality might affect the spatial presence a device provides regardless its display properties. This shows that determining the degree of immersion of a multi-XR device is not straightforward. Therefore, the concept of device-specific congruence (Latoschik & Wienrich, 2022) should continue to be specified and operationalized as an extension of immersion.

By using the VHPQ, we confirmed our hypothesis H1.2 and found no significant differences in the virtual alter ego's appearance and behavior plausibility. It suggests that the incongruence of having a rendered virtual alter ego within a real environment not clearly affects the internal consistency of a virtual alter ego's appearance and behavior. We further could confirm our hypothesis H1.3 by showing a significant impact of the virtual alter ego's match to the virtual environment between our VR and AR conditions. Hence, the priorly described mismatch in rendering realism is likely to affect the alter ego's plausibility. In VR, the congruence between the generation of virtual human and environment (both synthetic) resulted in a higher avatar plausibility, while the higher incongruence in the AR conditions (synthetic avatar vs. captured environment) led to a significant lower avatar plausibility. Considering the descriptive differences between VST AR and OST AR, we even assume that device-specific congruencies (captured environment vs. real environment) could have impacted the avatar plausibility. However, there was no significant statistical difference.

To summarize on RQ1, we can fully confirm our previous assumptions about the influence of different congruencies on spatial presence and avatar plausibility. Thus, we also can confirm the respective parts of Latoschik and Wienrich's novel theoretical model. Our results further are in line with the recently introduced taxonomy of Skarbez et al. (2021b) for describing XR experiences. However, during our study design, we noted that an update and revalidation of relevant measurement tools in line with recently updated concepts (Latoschik & Wienrich, 2022; Skarbez et al., 2021b; Wienrich et al., 2021b), like Mal et al. (2022) already did for avatar plausibility, seems timely. Here, it seems worth considering the work of Brübach et al. (2022), which was published after the conception of our study.

5.5.2 Virtual Human Perception

Body Weight Perception

Although we could not fully confirm our initial hypothesis H2.1, our results on body weight perception have various valuable implications. We could confirm prior findings of Wolf et al. (2022b) and show significant differences between VR and VST AR in comparison to OST AR. While our initial hypothesis was formulated under the assumption that both the displays' immersion and the provided congruence of the XR experience might impact body weight perception, our findings point to immersion as the main moderator. Our work and Wolf et al. (2022b) found significant differences between the used HMD devices (here XR-3 vs. HoloLens 2 and in Wolf et al. Vive Pro vs. HoloLens 2). It suggests that explicitly hardware-specific factors (e.g., built-in lenses, FoV, resolution of the display and its luminosity, or transparency of the rendered content) contribute to the perceptual differences. Adams et al. (2022) suggested similar as they found differences in distance perception between XR-3 and HoloLens 2. It raises the question of whether distorted distance perception might lead to a distorted body weight perception. Future research needs to address this question.

Exploring body weight perception regarding the performed body weight modification and gender provided further valuable insights. First, we showed that the body weight modification of the virtual alter ego had no significant effect on the estimators' body weight misestimations M. This is in line with Wolf et al. (2021), who showed a significant moderation of body weight misestimations by the body weight difference between estimator and avatar only when the estimator embodied the avatar. Therefore, we consider our decision not to employ full-body illusions to be justified.

Second, while we observed differences in body weight misestimations $\overline{\mathrm{M}}$ (averaging over- and underestimations across all nine modifications) between displays, we could not find differences in the absolute body weight misestimations $\overline{\mathrm{A}}$ (considering only the absolute magnitude per misestimations). In other words, the inaccuracy of individual estimations appears constant between displays, whereas the overall impression of body weight seems to differ. Hence, we assume that display-related body weight misperceptions are unlikely dependent on the stimulus's body weight (modification).

Third, the absolute body weight misestimations $\overline{\mathrm{A}}$ follow a pattern independent of the used display, as they become descriptively less accurate with increasing body weight deviation between stimulus and observer. This observation is consistent with the theory of contraction bias (K. K. Cornelissen et al., 2015, 2016), which states that body weight estimates are the most accurate around a subjective mental reference model of a body. For personalized, photorealistic virtual alter egos, it could be the own body since estimates are most accurate around there. Considering Weber's Law (K. K. Cornelissen et al., 2016), which assumes that changes in body weight are more difficult to detect when body weight increases, it is surprising that the contraction bias is significantly more pronounced in the case of a negative body weight modification.

Fourth, we showed no significant gender differences in the body weight estimations. Prior work repeatedly reported gender differences generally (Connor-Greene, 1988; Hsu, 1989; Paeratakul et al., 2002) but also in the context of virtual alter egos (Thaler et al., 2018b). As the prior work often refers to samples with eating- or body weight disorders, we attribute the differences to our sample.

Affective Appraisal

Regarding the affective appraisal of the virtual alter egos depending on our differently immersive and congruent XR experiences, we confirm our hypotheses H3.1, H3.2, and H3.3. Although the expected manipulation of the spatial presence of the XR experience and the plausibility of the virtual alter ego was successful, we found no influence of the manipulation on the perceived humanness, attractiveness, and eeriness. Therefore, we assume that the differences in immersion and congruence between our XR experiences are unlikely to affect the affective appraisal of our virtual alter egos. These results are not unexpected since previous work has found no differences between even more differently immersive systems for virtual humans perceived to be outside the uncanny valley (Hepperle et al., 2020). When considering the absolute judgments of affective appraisal in our study, especially for uncanniness, we would not locate the perception of our virtual alter ego in the uncanny valley. Nevertheless, our comparison offers novel insights regarding the perception of virtual alter egos since we are not aware of any other work investigating their affective appraisal between differently congruent XR experiences. Further research needs to confirm our findings.

5.5.3 Limitation and Future Work

Our work has several limitations that need to be addressed in future work. First, we could confirm our assumptions regarding the virtual alter ego's match to the virtual environment between our conditions (H1.2). However, since the avatar's shadow was only rendered in the VR conditions, we had a confound between VR and AR, which was not directly due to the display type. Therefore, future work will need to address the role of shadow casting in avatar plausibility.

Second, we controlled the extent of world knowledge as best as possible between conditions. Nevertheless, there still were differences, such as the lack of a representation of the own body in VR while it was visible in AR, that might have affected the congruence of the XR experiences further. Future work should therefore include the influence of the extent of world knowledge.

Third, we decided to use personalized virtual alter egos to control for various factors influencing virtual human perception. However, using alter egos instead of generic virtual humans may also impact perception due to the individual's body image. While it seems almost impossible to control all possible influencing factors in a single experimental design, future work should continue to address the influence of personalization.

Fourth, we assessed the affective appraisal of the virtual alter ego on the sub-dimensions of humanness, eeriness, and attractiveness and found no differences between displays. However, the appraisal of an experience is certainly not limited to these three factors but may also include factors such as emotional response. Here, previous work provides indications of differences in dependence on the display technology used (Waltemate et al., 2018). Hence, future work should also consider other factors like the emotional appraisal.

Finally, we identified immersion-related factors as possible reason causing differences in body weight perception but could not pinpoint a specific factor with our device-based manipulation. Hence, our results are bound to the properties of our tested devices (see Table C5.1). Future work should investigate the influence of distinct properties of immersion. Furthermore, it should be ruled out that immersion affects body weight perception via differently pronounced distance compression effects between different display devices.

5.6 Contribution and Conclusion

The rapid technical development of XR HMDs leads to a variety of differently immersive and congruent XR experiences. As a consequence, research faces the challenge that gained knowledge from one kind of experience might not be transferable to another one. Our work has addressed this challenge for the perception of virtual humans. To the best of our knowledge, we are the first to explore the plausibility and affective appraisal of virtual humans between different XR experiences. Furthermore, we confirm assumptions that body weight perception can be highly distorted between different XR HMDs by adding a comprehensive study design addressing the limitations of prior work. Hence, we suggest body weight perception as an interval scaled measure offering a nuanced perspective on possible display distortion effects beyond item-based questionnaires like those used for spatial presence and avatar plausibility. Although we worked with virtual alter egos in our study, we expect that the findings are largely transferable to the perception and plausibility of virtual humans and avatars.

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Author Contributions

Erik Wolf conceptualized large parts of the experimental design, collected parts of the data, performed the data analysis, and took the lead in writing the manuscript. Viktor Frohnapfel supported the conceptualization of the experimental design, adapted the Unity application for the experiment, collected parts of the data, and supported the data analysis. Erik Wolf and David Mal developed the Unity application. Mario Botsch and Stephan Wenninger provided the framework for the reconstruction of the avatars as well as their integration and realistic body weight modification in Unity. Carolin Wienrich and Marc Erich Latoschik conceived the original project idea, discussed the study design, and supervised the project. All authors continuously provided constructive feedback and helped to shape the study and the corresponding manuscript.

References

Achenbach, J., Brylka, R., Gietzen, T., Hebel, K., Schömer, E., Schulze, R., Botsch, M., & Schwanecke, U. (2018). A multilinear model for bidirectional craniofacial reconstruction. *Eurographics Workshop on Visual Computing for Biology and Medicine*, 67–76. https://doi.org/10.2312/vcbm.20181230 (cit. on p. 87).

Achenbach, J., Waltemate, T., Latoschik, M. E., & Botsch, M. (2017). Fast generation of realistic virtual humans. *Proceedings of the 23rd ACM Symposium on Virtual Reality Software and Technology*, 1–10. https://doi.org/10.1145/3139131.3139154 (cit. on pp. 7, 8, 26, 55, 62, 137, 164, 194).

Adams, H., Stefanucci, J., Creem-Regehr, S., & Bodenheimer, B. (2022). Depth perception in augmented reality: The effects of display, shadow, and position. *2022 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, 792–801. https://doi.org/10.1109/VR51125.2022.00101 (cit. on pp. 40, 203).

Agisoft. (2021). *Metashape Pro* (Version 1.7.0) [Computer software]. http://www.agisoft.com (cit. on pp. 62, 137).

Alcañiz, M., Perpiñá, C., Baños, R., Lozano, J. A., Montesa, J., Botella, C., Palacios, A. G., Villa, H., & Alozano, J. (2000). A new realistic 3D body representation in virtual environments for the treatment of disturbed body image in eating disorders. *Cyberpsychology & Behavior*, *3*(3), 433–439. https://doi.org/10.1089/10949310050078896 (cit. on p. 56).

Allen, B., Curless, B., & Popović, Z. (2003). The space of human body shapes: Reconstruction and parameterization from range scans. *ACM Trans. Graph.*, *22*(3), 587–594. https://doi.org/10.1145/882262.882311 (cit. on p. 139).

Alleva, J. M., Sheeran, P., Webb, T. L., Martijn, C., & Miles, E. (2015). A meta-analytic review of stand-alone interventions to improve body image. *PLOS ONE*, *10*(9), e0139177. https://doi.org/10.1371/journal.pone.0139177 (cit. on p. 55).

Angelov, V., Petkov, E., Shipkovenski, G., & Kalushkov, T. (2020). Modern virtual reality headsets. *2020 International Congress on Human-Computer Interaction, Optimization and Robotic Applications (HORA)*, 1–5. https://doi.org/10.1109/HORA49412.2020.9152604 (cit. on pp. 3, 124, 152).

Anguelov, D., Srinivasan, P., Koller, D., Thrun, S., Rodgers, J., & Davis, J. (2005). Scape: Shape completion and animation of people. *ACM Trans. Graph.*, *24*(3), 408–416. https://doi.org/10.1145/1073204.1073207 (cit. on p. 63).

Apple. (2022). *Apple Vision Pro*. https://www.apple.com/apple-vision-pro (cit. on p. 42).

Aristidou, A., Lasenby, J., Chrysanthou, Y., & Shamir, A. (2018). Inverse kinematics techniques in computer graphics: A survey. *Computer Graphics Forum*, *37*(6), 35–58. https://doi.org/10.1111/cgf.13310 (cit. on pp. 26, 42, 48, 62, 138).

Arnold, A. G. (1999). Mental effort and evaluation of user-interfaces: A questionnaire approach. *Proceedings of HCI International (the 8th International Conference on Human-Computer Interaction) on Human-Computer Interaction: Ergonomics and User Interfaces-Volume I*, 1003–1007 (cit. on pp. 69, 134).

Autodesk. (2014). *Character Generator* [Computer software]. https://charactergenerator.autodesk.com (cit. on pp. 7, 62, 194).

Aymerich-Franch, L. (2020). Chapter 3 – Avatar embodiment experiences to enhance mental health. In J. Kim & H. Song (Eds.), *Technology and health* (pp. 49–66). Academic Press. https://doi.org/10.1016/B978-0-12-816958-2.00003-4 (cit. on p. 123).

Bailenson, J. N., & Blascovich, J. (2004). Avatars. In *Encyclopedia of human-computer interaction* (pp. 64–68). Berkshire Publishing Group. https://stanfordvr.com/mm/2004/bailenson-avatars.pdf (cit. on pp. 6, 55, 98, 122, 184).

Banakou, D., Groten, R., & Slater, M. (2013). Illusory ownership of a virtual child body causes overestimation of object sizes and implicit attitude changes. *Proceedings of the National Academy of Sciences*, *110*(31), 12846–12851. https://doi.org/10.1073/pnas.1306779110 (cit. on p. 12).

Banakou, D., Hanumanthu, P. D., & Slater, M. (2016). Virtual embodiment of white people in a black virtual body leads to a sustained reduction in their implicit racial bias. *Frontiers in Human Neuroscience*, *10*. https://doi.org/10.3389/fnhum.2016.00601 (cit. on p. 11).

Banakou, D., Kishore, S., & Slater, M. (2018). Virtually being einstein results in an improvement in cognitive task performance and a decrease in age bias. *Frontiers in Psychology*, *9*. https://doi.org/10.3389/fpsyg.2018.00917 (cit. on p. 11).

Bartl, A., Jung, S., Kullmann, P., Wenninger, S., Achenbach, J., Wolf, E., Schell, C., Lindeman, R. W., Botsch, M., & Latoschik, M. E. (2021a). Self-avatars in virtual reality: A study protocol for investigating the impact of the deliberateness of choice and the context-match. *2021 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW)*, 565–566. https://doi.org/10.1109/VRW52623.2021.00165 (cit. on pp. 49, 247).

Bartl, A., Merz, C., Roth, D., & Latoschik, M. E. (2022). The effects of avatar and environment design on embodiment, presence, activation, and task load in a virtual reality exercise application. *2022 IEEE International Symposium on Mixed and Augmented Reality (ISMAR)*, 260–269. https://doi.org/10.1109/ISMAR55827.2022.00041 (cit. on pp. 22, 45, 149).

Bartl, A., Wenninger, S., Wolf, E., Botsch, M., & Latoschik, M. E. (2021b). Affordable but not cheap: A case study of the effects of two 3D-reconstruction methods of virtual humans. *Frontiers in Virtual Reality*, *2*. https://doi.org/10.3389/frvir.2021.694617 (cit. on pp. 8, 21, 27, 49, 55, 62, 81, 86, 129, 130, 137, 153, 178, 185, 189, 194, 248).

Bauer, A., Schneider, S., Waldorf, M., Braks, K., Huber, T. J., Adolph, D., & Vocks, S. (2017). Selective visual attention towards oneself and associated state body satisfaction: An eye-tracking study in adolescents with different types of eating disorders. *Journal of abnormal child psychology*, *45*(8), 1647–1661. https://doi.org/10.1007/s10802-017-0263-z (cit. on pp. 38, 151).

Bierhoff, H.-W. (1989). *Person perception and attribution*. Springer Berlin, Heidelberg. https://doi.org/10.1007/978-3-642-74130-2 (cit. on p. 14).

Bimberg, P., Weissker, T., & Kulik, A. (2020). On the usage of the simulator sickness questionnaire for virtual reality research. *2020 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW)*, 464–467. https://doi.org/10.1109/VRW50115.2020.00098 (cit. on pp. 69, 135, 167, 192).

Blanca Mena, M. J., Alarcón Postigo, R., Arnau Gras, J., Bono Cabré, R., & Bendayan, R. (2017). Non-normal data: Is anova still a valid option? *Psicothema*, *29*(4), 552–557. https://doi.org/10.7334/psicothema2016.383 (cit. on p. 169).

Blender Foundation. (2019). *Blender* (Version 2.79b) [Computer software]. https://blender.org (cit. on p. 102).

Botsch, M., Kobbelt, L., Pauly, M., Alliez, P., & Lévy, B. (2010). *Polygon mesh processing*. AK Peters, CRC press. https://doi.org/10.1201/b10688 (cit. on p. 64).

Botsch, M., & Sorkine, O. (2008). On linear variational surface deformation methods. *IEEE Transactions on Visualization and Computer Graphics*, *14*(1), 213–230. https://doi.org/10.1109/TVCG.2007.1054 (cit. on p. 64).

Botvinick, M., & Cohen, J. (1998). Rubber hands 'feel' touch that eyes see. *Nature*, *391*(6669), 756–756. https://doi.org/10.1038/35784 (cit. on pp. 10, 98).

Bouaziz, S., Tagliasacchi, A., & Pauly, M. (2014). Dynamic 2D/3D registration. *Eurographics Tutorials*, 1–17. https://doi.org/10.1145/2504435.2504456 (cit. on p. 62).

Bouchard, S., Robillard, G., St-Jacques, J., Dumoulin, S., Patry, M.-J., & Renaud, P. (2004). Reliability and validity of a single-item measure of presence in VR. *Proceedings of the Second International Conference on Creating, Connecting and Collaborating through Computing*, 59–61. https://doi.org/10.1109/HAVE.2004.1391882 (cit. on pp. 105, 167).

Bouchard, S., St-Jacques, J., Robillard, G., & Renaud, P. (2008). Anxiety increases the feeling of presence in virtual reality. *Presence: Teleoperators & Virtual Environments*, *17*(4), 376–391. https://doi.org/10.1162/pres.17.4.376 (cit. on pp. 105, 167).

Bourdin, P., Barberia, I., Oliva, R., & Slater, M. (2017). A virtual out-of-body experience reduces fear of death. *PLOS ONE*, *12*(1), 1–19. https://doi.org/10.1371/journal.pone.0169343 (cit. on p. 22).

Bracken, C. C. (2005). Presence and image quality: The case of high-definition television. *Media Psychology*, *7*(2), 191–205. https://doi.org/10.1207/S1532785XMEP0702_4 (cit. on p. 2).

Braun, V., & Clarke, V. (2006). Using thematic analysis in psychology. *Qualitative Research in Psychology*, *3*(2), 77–101. https://doi.org/10.1191/1478088706qp063oa (cit. on pp. 50, 172).

Brenner, E., & van Damme, W. J. (1999). Perceived distance, shape and size. *Vision Research*, *39*(5), 975–986. https://doi.org/10.1016/S0042-6989(98)00162-X (cit. on p. 150).

Brübach, L., Westermeier, F., Wienrich, C., & Latoschik, M. E. (2022). Breaking plausibility without breaking presence – Evidence for the multi-layer nature of plausibility. *IEEE Transactions on Visualization and Computer Graphics*, *28*(5), 2267–2276. https://doi.org/10.1109/TVCG.2022.3150496 (cit. on pp. 6, 203).

Buck, L. E., Young, M. K., & Bodenheimer, B. (2018). A comparison of distance estimation in HMD-based virtual environments with different HMD-based conditions. *ACM Transactions on Applied Perception (TAP)*, *15*(3). https://doi.org/10.1145/3196885 (cit. on pp. 31, 148).

Burdea, G. C., & Coiffet, P. (2003). *Virtual reality technology*. John Wiley & Sons. https://www.wiley.com/en-us/Virtual+Reality+Technology%2C+2nd+Edition-p-9781119485728 (cit. on pp. 2, 98).

Burden, D., & Savin-Baden, M. (2019). *Virtual humans: Today and tomorrow*. Chapman; Hall/CRC. https://doi.org/10.1201/9781315151199 (cit. on pp. 6, 7).

Buttussi, F., & Chittaro, L. (2018). Effects of different types of virtual reality display on presence and learning in a safety training scenario. *IEEE Transactions on Visualization and Computer Graphics*, *24*(2), 1063–1076. https://doi.org/10.1109/TVCG.2017.2653117 (cit. on pp. 27, 46, 82).

Captury. (2021). *Captury Live* (Version 229) [Computer software]. https://captury.com (cit. on pp. 32, 42, 48, 159, 162).

Cash, T. F., & Deagle III, E. A. (1997). The nature and extent of body-image disturbances in anorexia nervosa and bulimia nervosa: A meta-analysis. *International Journal of Eating Disorders*, *22*(2), 107–126. https://doi.org/10.1002/(SICI)1098-108X(199709)22:2<107::AID-EAT1>3.0.CO;2-J (cit. on p. 8).

Castelfranchi, C. (2000). Affective appraisal versus cognitive evaluation in social emotions and interactions. In A. Paiva (Ed.), *Affective interactions: Towards a new generation of computer interfaces* (pp. 76–106). Springer Berlin Heidelberg. https://doi.org/10.1007/10720296_7 (cit. on p. 21).

Caudell, T., & Mizell, D. (1992). Augmented reality: An application of heads-up display technology to manual manufacturing processes. *Proceedings of the Twenty-Fifth Hawaii International Conference on System Sciences*, *2*, 659–669. https://doi.org/10.1109/HICSS.1992.183317 (cit. on p. 3).

Chaminade, T., Hodgins, J., & Kawato, M. (2007). Anthropomorphism influences perception of computer-animated characters' actions. *Social cognitive and affective neuroscience*, *2*(3), 206–216. https://doi.org/10.1093/scan/nsm017 (cit. on pp. 21, 129, 189).

Chicchi Giglioli, I. A., Bermejo Vidal, C., & Alcañiz Raya, M. (2019). A virtual versus an augmented reality cooking task based-tools: A behavioral and physiological study on the assessment of executive functions. *Frontiers in Psychology*, *10*, 2529. https://doi.org/10.3389/fpsyg.2019.02529 (cit. on pp. 3, 33, 34, 160, 165, 174, 196).

Cohen, J. (2013). *Statistical power analysis for the behavioral sciences*. Academic press. https://doi.org/10.4324/9780203771587 (cit. on pp. 111, 112, 143, 171).

Connor-Greene, P. A. (1988). Gender differences in body weight perception and weight-loss strategies of college students. *Women & Health*, *14*(2), 27–42. https://doi.org/10.1300/J013v14n02_03 (cit. on pp. 15, 104, 164, 204).

Cooper, P. J., Taylor, M. J., Cooper, Z., & Fairbum, C. G. (1987). The development and validation of the body shape questionnaire. *International Journal of Eating Disorders*, *6*(4), 485–494. https://doi.org/10.1002/1098-108X(198707)6:4<485::AID-EAT2260060405>3.0.CO;2-O (cit. on pp. 106, 135, 167).

Cornelissen, K. K., Bester, A., Cairns, P., Tovée, M. J., & Cornelissen, P. L. (2015). The influence of personal BMI on body size estimations and sensitivity to body size change in anorexia spectrum disorders. *Body Image*, *13*, 75–85. https://doi.org/10.1016/j.bodyim.2015.01.001 (cit. on pp. 15, 27, 36, 43, 85, 204).

Cornelissen, K. K., Gledhill, L. J., Cornelissen, P. L., & Tovée, M. J. (2016). Visual biases in judging body weight. *British Journal of Health Psychology*, *21*(3), 555–569. https://doi.org/10.1111/bjhp.12185 (cit. on pp. 15, 27, 35–37, 43, 85, 188, 204).

Cornelissen, P. L., Cornelissen, K. K., Groves, V., McCarty, K., & Tovée, M. J. (2018). View-dependent accuracy in body mass judgements of female bodies. *Body Image*, *24*, 116–123. https://doi.org/10.1016/j.bodyim.2017.12.007 (cit. on pp. 23, 85, 141, 188, 191).

Corno, G., Serino, S., Cipresso, P., Baños, R. M., & Riva, G. (2018). Assessing the relationship between attitudinal and perceptual component of body image disturbance using virtual reality. *Cyberpsychology, Behavior, and Social Networking*, *21*(11), 679–686. https://doi.org/10.1089/cyber.2018.0340 (cit. on p. 96).

Crossley, K. L., Cornelissen, P. L., & Tovée, M. J. (2012). What is an attractive body? Using an interactive 3D program to create the ideal body for you and your partner. *PLOS ONE*, *7*(11), 1–11. https://doi.org/10.1371/journal.pone.0050601 (cit. on p. 8).

Cruz-Neira, C., Sandin, D. J., DeFanti, T. A., Kenyon, R. V., & Hart, J. C. (1992). The CAVE: Audio visual experience automatic virtual environment. *Commun. ACM*, *35*(6), 64–72. https://doi.org/10.1145/129888.129892 (cit. on p. 3).

Cummings, J. J., & Bailenson, J. N. (2016). How immersive is enough? A meta-analysis of the effect of immersive technology on user presence. *Media Psychology*, *19*(2), 272–309. https://doi.org/10.1080/15213269.2015.1015740 (cit. on pp. 3, 33, 34, 47, 160, 165, 174, 196).

DAZ Productions. (2005). *DAZ Studio* [Computer software]. https://www.daz3d.com/ (cit. on p. 8).

De Greef, S., Claes, P., Vandermeulen, D., Mollemans, W., Suetens, P., & Willems, G. (2006). Large-scale in-vivo caucasian facial soft tissue thickness database for craniofacial reconstruction. *Forensic Science International*, *159*, 126–146. https://doi.org/10.1016/j.forsciint.2006.02.034 (cit. on p. 87).

de Vignemont, F. (2011). Embodiment, ownership and disownership. *Consciousness and Cognition*, *20*(1), 82–93. https://doi.org/10.1016/j.concog.2010.09.004 (cit. on p. 10).

Debarba, H. G., Molla, E., Herbelin, B., & Boulic, R. (2015). Characterizing embodied interaction in first and third person perspective viewpoints. *2015 IEEE Symposium on 3D User Interfaces (3DUI)*, 67–72. https://doi.org/10.1109/3DUI.2015.7131728 (cit. on pp. 10, 22, 29, 122, 133).

Debarba, H. G., Bovet, S., Salomon, R., Blanke, O., Herbelin, B., & Boulic, R. (2017). Characterizing first and third person viewpoints and their alternation for embodied interaction in virtual reality. *PLOS ONE*, *12*(12), 1–19. https://doi.org/10.1371/journal.pone.0190109 (cit. on pp. 22, 31, 127, 148, 149).

Delinsky, S. S., & Wilson, G. T. (2006). Mirror exposure for the treatment of body image disturbance. *International Journal of Eating Disorders*, *39*(2), 108–116. https://doi.org/10.1002/eat.20207 (cit. on pp. 9, 23, 123).

Diel, A., Weigelt, S., & Macdorman, K. F. (2021). A meta-analysis of the uncanny valley's independent and dependent variables. *ACM Transactions on Human-Robot Interaction (THRI)*, *11*(1). https://doi.org/10.1145/3470742 (cit. on p. 21).

Diemer, J., Alpers, G. W., Peperkorn, H. M., Shiban, Y., & Mühlberger, A. (2015). The impact of perception and presence on emotional reactions: A review of research in virtual reality. *Frontiers in Psychology*, *6*, 26. https://doi.org/10.3389/fpsyg.2015.00026 (cit. on pp. 3, 98).

Docteur, A., Urdapilleta, I., Defrance, C., & Raison, J. (2010). Body perception and satisfaction in obese, severely obese, and normal weight female patients. *Obesity*, *18*(7), 1464–1465. https://doi.org/10.1038/oby.2009.418 (cit. on pp. 15, 56).

Doerner, R., Broll, W., Grimm, P., & Jung, B. (2022). *Virtual and augmented reality (VR/AR): Foundations and methods of extended realities (XR)*. Springer Nature. https://doi.org/10.1007/978-3-030-79062-2 (cit. on pp. 2, 6).

Döllinger, N., Beck, M., Wolf, E., Mal, D., Botsch, M., Latoschik, M. E., & Wienrich, C. (2023a). "If it's not me it doesn't make a difference" – The impact of avatar customization and personalization on user experience and body awareness in virtual reality. *2023 IEEE International Symposium on Mixed and Augmented Reality (ISMAR)*. https://doi.org/10.1109/ISMAR59233.2023.00063 (cit. on pp. 49, 249).

Döllinger, N., Göttfert, C., Wolf, E., Mal, D., Latoschik, M. E., & Wienrich, C. (2022a). Analyzing eye tracking data in mirror exposure. *Proceedings of the Conference on Mensch und Computer*, *Proceedings of Mensch Und Computer 2022*, 513–517. https://doi.org/10.1145/3543758.3547567 (cit. on p. 248).

Döllinger, N., Mal, D., Keppler, S., Wolf, E., Botsch, M., Israel, J. H., Latoschik, M. E., & Wienrich, C. (2024a). Virtual body swapping: A VR-based approach to embodied third-person self-processing in mind-body therapy, 1–18. https://doi.org/10.1145/3613904.3642328 (cit. on pp. 48, 49, 249).

Döllinger, N., Mal, D., Sinn, M., Wolf, E., Wienrich, C., & Latoschik, M. E. (2024b). The effect of delay on virtual body ownership and body awareness [Manuscript in preparation for publication] (cit. on pp. 49, 250).

Döllinger, N., Wienrich, C., Wolf, E., & Latoschik, M. E. (2019). ViTraS – Virtual reality therapy by stimulation of modulated body image – Project outline. *Mensch und Computer 2019 – Workshopband*, 1–6. https://doi.org/10.18420/muc2019-ws-633 (cit. on pp. 9, 21, 25, 55, 56, 59, 67, 87, 96, 123, 159, 178, 184, 247).

Döllinger, N., Wolf, E., Botsch, M., Latoschik, M. E., & Wienrich, C. (2023b). Are embodied avatars harmful to our self-experience? The impact of virtual embodiment on body awareness. *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems*. https://doi.org/10.1145/3544548.3580918 (cit. on pp. 22, 45, 48, 149, 248).

Döllinger, N., Wolf, E., Mal, D., Erdmannsdörfer, N., Botsch, M., Latoschik, M. E., & Wienrich, C. (2022b). Virtual reality for mind and body: Does the sense of embodiment towards a virtual body affect physical body awareness? *Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems*, 1–8. https://doi.org/10.1145/3491101.3519613 (cit. on pp. 48, 58, 87, 248).

Döllinger, N., Wolf, E., Mal, D., Wenninger, S., Botsch, M., Latoschik, M. E., & Wienrich, C. (2022c). Resize me! Exploring the user experience of embodied realistic modulatable avatars for body image intervention in virtual reality. *Frontiers in Virtual Reality*, *3*. https://doi.org/10.3389/frvir.2022.935449 (cit. on pp. 24, 53, 123, 128–130, 134, 136, 139–141, 151, 184, 185, 188, 189, 191, 192, 194, 195).

Dooley, M. (1982). Anthropometric modeling programs – A survey. *IEEE Computer Graphics and Applications*, *2*(9), 17–25. https://doi.org/10.1109/MCG.1982.1674472 (cit. on p. 7).

Du, Y., Kips, R., Pumarola, A., Starke, S., Thabet, A., & Sanakoyeu, A. (2023). Avatars grow legs: Generating smooth human motion from sparse tracking inputs with diffusion model. *Proceedings of the IEEE/CVF Conference on Computer Vision and Pattern Recognition (CVPR)*, 481–490. https://doi.org/10.48550/arXiv.2304.08577 (cit. on p. 51).

Dunn, R. A., & Guadagno, R. E. (2012). My avatar and me – Gender and personality predictors of avatar-self discrepancy. *Computers in Human Behavior*, *28*(1), 97–106. https://doi.org/10.1016/j.chb.2011.08.015 (cit. on p. 17).

Dupraz, L., Barra, J., Beaudoin, M., & Guerraz, M. (2023). Impact of an overweight body representation in virtual reality on locomotion in a motor imagery task. *Psychological Research*, *87*(2), 462–473. https://doi.org/10.1007/s00426-022-01675-x (cit. on p. 11).

Eckstein, B., Krapp, E., Elsässer, A., & Lugrin, B. (2019). Smart substitutional reality: Integrating the smart home into virtual reality. *Entertainment Computing*, *31*, 100306. https://doi.org/10.1016/j.entcom.2019.100306 (cit. on p. 102).

Edwards, E., Rolland, J., & Keller, K. (1993). Video see-through design for merging of real and virtual environments. *Proceedings of IEEE Virtual Reality Annual International Symposium*, 223–233. https://doi.org/10.1109/VRAIS.1993.380774 (cit. on p. 3).

Eilers, K., Nachreiner, F., & Hänecke, K. (1986). Entwicklung und überprüfung einer skala zur erfassung subjektiv erlebter anstrengung. *Zeitschrift für Arbeitswissenschaft*, (4), 214–224. https://www.arbeitswissenschaft.net (cit. on pp. 69, 134).

Epic Games. (2021a). *Meta Human* [Computer software]. https://unrealengine.com/en-US/digital-humans (cit. on pp. 8, 83).

Epic Games. (2021b). *Unreal Engine* (Version 5.0.0) [Computer software]. https://www.unrealengine.com/de (cit. on p. 2).

Epstein, R. A., Patai, E. Z., Julian, J. B., & Spiers, H. J. (2017). The cognitive map in humans: Spatial navigation and beyond. *Nature Neuroscience*, *20*(11), 1504–1513. https://doi.org/10.1038/nn.4656 (cit. on p. 125).

Ernst, M. O. (2008). Multisensory integration: A late bloomer. *Current Biology*, *18*(12), R519–R521. https://doi.org/10.1016/j.cub.2008.05.002 (cit. on p. 2).

Evans, C., & Dolan, B. (1993). Body shape questionnaire: Derivation of shortened "alternate forms". *International Journal of Eating Disorders*, *13*(3), 315–321. https://doi.org/10.1002/1098-108X(199304)13:3<315::AID-EAT2260130310>3.0.CO;2-3 (cit. on pp. 106, 135, 167).

Farrell, C., Shafran, R., & Lee, M. (2006). Empirically evaluated treatments for body image disturbance: A review. *European Eating Disorders Review*, *14*(5), 289–300. https://doi.org/10.1002/erv.693 (cit. on p. 56).

Faul, F., Erdfelder, E., Buchner, A., & Lang, A.-G. (2009). Statistical power analyses using G*Power 3.1: Tests for correlation and regression analyses. *Behavior research methods*, *41*(4), 1149–1160. https://gpower.hhu.de/ (cit. on pp. 109, 143, 169).

Ferrer-Garcia, M., Gutierrez-Maldonado, J., Caqueo-Urizar, A., & Moreno, E. (2009). The validity of virtual environments for eliciting emotional responses in patients with eating disorders and in controls. *Behavior Modification*, *33*(6), 830–854. https://doi.org/10.1177/0145445509348056 (cit. on p. 56).

Ferrer-Garcia, M., Gutiérrez-Maldonado, J., & Riva, G. (2013). Virtual reality based treatments in eating disorders and obesity: A review. *Journal of Contemporary Psychotherapy*, *43*(4), 207–221. https://doi.org/10.1007/s10879-013-9240-1 (cit. on pp. 55, 56).

Ferrer-Garcia, M., Porras-Garcia, B., Moreno, M., Bertomeu, P., Maldonado, J., Ferrer-Garcia, M., Porras-Garcia, B., Moreno, M., Bertomeu, P., & Gutierrez Maldonado, J. (2018). Embodiment in different size virtual bodies produces changes in women's body image distortion and dissatisfaction. *Annual Review of Cybertherapy and Telemedicine 2018*, *16*, 111. http://hdl.handle.net/2445/155443 (cit. on p. 56).

Ferring, D., & Filipp, S.-H. (1996). Messung des selbstwertgefühls: Befunde zu reliabilität, validität und stabilität der Rosenberg-Skala. *Diagnostica-Goettingen*, *42*, 284–292. https://psycnet.apa.org/record/1996-94139-005 (cit. on pp. 106, 135, 167).

Fiedler, M. L., Wolf, E., Döllinger, N., Botsch, M., Latoschik, M. E., & Wienrich, C. (2023a). Embodiment and personalization for self-identification with virtual humans. *2023 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW)*, 799–800. https://doi.org/10.1109/VRW58643.2023.00242 (cit. on pp. 21, 23, 37, 48, 127, 248).

Fiedler, M. L., Wolf, E., Döllinger, N., Mal, D., Botsch, M., Latoschik, M. E., & Wienrich, C. (2024). From avatars to agents: Self-related cues through embodiment and personalization affect body perception in virtual reality. *IEEE Transactions on Visualization and Computer Graphics*, 1–11. https://doi.org/10.1109/TVCG.2024.3456211 (cit. on pp. 49, 249).

Fiedler, M. L., Wolf, E., Wienrich, C., & Latoschik, M. E. (2023b). Holographic augmented reality mirrors for daily self-reflection on the own body image. *Integrating Individual and Social Contexts into Self-Reflection Technologies Workshop (WS28, CHI '23)*. https://downloads.hci.informatik.uni-wuerzburg.de/2023-chi-reflection-workshop.pdf (cit. on pp. 8, 12, 249).

Field, A. (2017). *Discovering statistics using IBM SPSS statistics* (Vol. 5). Sage Publications Ltd. https://uk.sagepub.com/en-gb/eur/discovering-statistics-using-ibm-spss-statistics/book257672 (cit. on p. 198).

Fildes, A., Charlton, J., Rudisill, C., Littlejohns, P., Prevost, A. T., & Gulliford, M. C. (2015). Probability of an obese person attaining normal body weight: Cohort study using electronic health records. *American Journal of Public Health*, *105*(9), e54–e59. https://doi.org/10.2105/AJPH.2015.302773 (cit. on p. 8).

Filippetti, M. L., & Tsakiris, M. (2017). Heartfelt embodiment: Changes in body-ownership and self-identification produce distinct changes in interoceptive accuracy. *Cognition*, *159*, 1–10. https://doi.org/10.1016/j.cognition.2016.11.002 (cit. on pp. 58, 84).

Foschi, M. (1996). Double standards in the evaluation of men and women. *Social Psychology Quarterly*, *59*(3), 237–254. https://doi.org/10.2307/2787021 (cit. on p. 37).

Gaggioli, A., Mantovani, F., Castelnuovo, G., Wiederhold, B., & Riva, G. (2003). Avatars in clinical psychology: A framework for the clinical use of virtual humans. *CyberPsychology & Behavior*, *6*(2), 117–125. https://doi.org/10.1089/109493103321640301 (cit. on p. 21).

Gall, D., Roth, D., Stauffert, J.-P., Zarges, J., & Latoschik, M. E. (2021). Embodiment in virtual reality intensifies emotional responses to virtual stimuli. *Frontiers in Psychology*, *12*, 3833. https://doi.org/10.3389/fpsyg.2021.674179 (cit. on p. 11).

Gemesi, K., Döllinger, N., Weinberger, N.-A., Erik, W., Mal, D., Wienrich, C., Luck-Sikorski, C., Bader, E., & Holzapfel, C. (2023). Auswirkung von (virtuellen) Körperbildübungen auf das Ernährungsverhalten von Personen mit Adipositas – Ergebnisse der ViTraS-Pilotstudie. *Adipositas - Ursachen, Folgeerkrankungen, Therapie*, *17*(03), S10–05. https://doi.org/10.1055/s-0043-1771568 (cit. on p. 249).

Genay, A. C. S., Lécuyer, A., & Hachet, M. (2021). Being an avatar "for real": A survey on virtual embodiment in augmented reality. *IEEE Transactions on Visualization and Computer Graphics*, *28*(12), 1–17. https://doi.org/10.1109/TVCG.2021.3099290 (cit. on pp. 12, 18, 19, 31, 46, 159–161, 165, 175, 177).

Gilinsky, A. S. (1951). Perceived size and distance in visual space. *Psychological Review*, *58*(6), 460. https://doi.org/10.1037/h0061505 (cit. on pp. 125, 150).

Glémarec, Y., Lugrin, J.-L., Bosser, A.-G., Buche, C., & Latoschik, M. E. (2022). Controlling the stage: A high-level control system for virtual audiences in virtual reality. *Frontiers in Virtual Reality*, *3*. https://doi.org/10.3389/frvir.2022.876433 (cit. on p. 8).

Gonzalez-Franco, M., Abtahi, P., & Steed, A. (2019). Individual differences in embodied distance estimation in virtual reality. *2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, 941–943. https://doi.org/10.1109/VR.2019.8798348 (cit. on pp. 31, 127, 128, 148).

Gonzalez-Franco, M., Ofek, E., Pan, Y., Antley, A., Steed, A., Spanlang, B., Maselli, A., Banakou, D., Pelechano, N., Orts-Escolano, S., Orvalho, V., Trutoiu, L., Wojcik, M., Sanchez-Vives, M. V., Bailenson, J., Slater, M., & Lanier, J. (2020a). The Rocketbox library and the utility of freely available rigged avatars. *Frontiers in Virtual Reality*, *1*. https://doi.org/10.3389/frvir.2020.561558 (cit. on p. 7).

Gonzalez-Franco, M., & Peck, T. C. (2018). Avatar embodiment. Towards a standardized questionnaire. *Frontiers in Robotics and AI*, *5*, 74. https://doi.org/10.3389/frobt.2018.00074 (cit. on p. 133).

Gonzalez-Franco, M., Steed, A., Hoogendyk, S., & Ofek, E. (2020b). Using facial animation to increase the enfacement illusion and avatar self-identification. *IEEE Transactions on Visualization and Computer Graphics*, *26*(5), 2023–2029. https://doi.org/10.1109/TVCG.2020.2973075 (cit. on pp. 16, 87).

Gorisse, G., Christmann, O., Amato, E. A., & Richir, S. (2017). First- and third-person perspectives in immersive virtual environments: Presence and performance analysis of embodied users. *Frontiers in Robotics and AI*, *4*. https://doi.org/10.3389/frobt.2017.00033 (cit. on pp. 22, 31, 127, 148, 149).

Gorisse, G., Christmann, O., Houzangbe, S., & Richir, S. (2018). From robot to virtual doppelganger: Impact of avatar visual fidelity and self-esteem on perceived attractiveness. https://doi.org/10.1145/3206505.3206525 (cit. on p. 17).

Gorisse, G., Christmann, O., Houzangbe, S., & Richir, S. (2019). From robot to virtual doppelganger: Impact of visual fidelity of avatars controlled in third-person perspective on embodiment and behavior in immersive virtual environments. *Frontiers in Robotics and AI*, *6*. https://doi.org/10.3389/frobt.2019.00008 (cit. on pp. 15, 21).

Griffen, T. C., Naumann, E., & Hildebrandt, T. (2018). Mirror exposure therapy for body image disturbances and eating disorders: A review. *Clinical Psychology Review*, *65*, 163–174. https://doi.org/10.1016/j.cpr.2018.08.006 (cit. on pp. 9, 23, 56, 123).

Halbig, A., Babu, S. K., Gatter, S., Latoschik, M. E., Brukamp, K., & von Mammen, S. (2022). Opportunities and challenges of virtual reality in healthcare – A domain experts inquiry. *Frontiers in Virtual Reality*, *3*. https://doi.org/10.3389/frvir.2022.837616 (cit. on p. 86).

Hanavan Jr, E. P. (1964). A mathematical model of the human body. https://apps.dtic.mil/sti/citations/AD0608463 (cit. on p. 7).

Hayes, A. F., & Cai, L. (2007). Using heteroskedasticity-consistent standard error estimators in ols regression: An introduction and software implementation. *Behavior research methods*, *39*(4), 709–722. https://doi.org/10.3758/BF03192961 (cit. on p. 79).

He, D., Liu, F., Pape, D., Dawe, G., & Sandin, D. (2000). Video-based measurement of system latency. *International Immersive Projection Technology Workshop*, 1–6. https://www.evl.uic.edu/documents/latency_ipt2000.pdf (cit. on pp. 60, 102, 136, 164).

Heeter, C. (1992). Being there: The subjective experience of presence. *Presence: Teleoperators & Virtual Environments*, *1*(2), 262–271. https://doi.org/10.1162/pres.1992.1.2.262 (cit. on p. 3).

Hendrix, C., & Barfield, W. (1996a). Presence within virtual environments as a function of visual display parameters. *Presence: Teleoperators and Virtual Environments*, *5*(3), 274–289. https://doi.org/10.1162/pres.1996.5.3.274 (cit. on p. 2).

Hendrix, C., & Barfield, W. (1996b). The sense of presence within auditory virtual environments. *Presence: Teleoperators and Virtual Environments*, *5*(3), 290–301. https://doi.org/10.1162/pres.1996.5.3.290 (cit. on p. 2).

Henrich, M., Kleespies, M. W., Dierkes, P. W., & Formella-Zimmermann, S. (2022). Inclusion of technology affinity in self scale – Development and evaluation of a single item measurement instrument for technology affinity. *Frontiers in Education*, *7*. https://doi.org/10.3389/feduc.2022.970212 (cit. on p. 17).

Hepperle, D., Ödell, H., & Wölfel, M. (2020). Differences in the uncanny valley between head-mounted displays and monitors. *2020 International Conference on Cyberworlds (CW)*, 41–48. https://doi.org/10.1109/CW49994.2020.00014 (cit. on pp. 21, 129, 185, 189, 196, 205).

Hepperle, D., Purps, C. F., Deuchler, J., & Wölfel, M. (2022). Aspects of visual avatar appearance: Self-representation, display type, and uncanny valley. *The Visual Computer*, *38*(4), 1227–1244. https://doi.org/10.1007/s00371-021-02151-0 (cit. on pp. 18, 21, 129, 185, 189).

Herrera, F., Bailenson, J., Weisz, E., Ogle, E., & Zaki, J. (2018). Building long-term empathy: A large-scale comparison of traditional and virtual reality perspective-taking. *PLOS ONE*, *13*(10), e0204494. https://doi.org/10.1371/journal.pone.0204494 (cit. on p. 185).

Higashiyama, A., & Shimono, K. (2004). Mirror vision: Perceived size and perceived distance of virtual images. *Perception & Psychophysics*, *66*(4), 679–691. https://doi.org/10.3758/BF03194911 (cit. on pp. 127, 128).

Ho, C.-C., & MacDorman, K. F. (2017). Measuring the uncanny valley effect. *International Journal of Social Robotics*, *9*(1), 129–139. https://doi.org/10.1007/s12369-016-0380-9 (cit. on pp. 69, 129, 135, 189, 192).

Horne, M., Hill, A., Murells, T., Ugail, H., Irving, D., Chinnadorai, R., & Hardy, M. (2020). Using avatars in weight management settings: A systematic review. *Internet Interventions*, *19*, 100295. https://doi.org/10.1016/j.invent.2019.100295 (cit. on pp. 9, 13, 15, 21, 41, 55–57, 82, 184, 188).

Hsu, L. K. G. (1989). The gender gap in eating disorders: Why are the eating disorders more common among women? *Clinical Psychology Review*, *9*(3), 393–407. https://doi.org/10.1016/0272-7358(89)90063-9 (cit. on pp. 15, 104, 204).

HTC. (2018a). *Vive Pro*. https://vive.com (cit. on pp. 18, 38, 102).

HTC. (2018b). *Vive Pro Eye*. https://www.vive.com/us/newsroom/2019-06-06/ (cit. on p. 48).

Hudson, G. M., Lu, Y., Zhang, X., Hahn, J., Zabal, J. E., Latif, F., & Philbeck, J. (2020). The development of a BMI-guided shape morphing technique and the effects of an individualized figure rating scale on self-perception of body size. *European Journal of Investigation in Health, Psychology and Education*, *10*(2), 579–594. https://doi.org/10.3390/ejihpe10020043 (cit. on pp. 9, 55, 56).

IBM. (2019). *SPSS Statistics* (Version 26.0.X.X) [Computer software]. https://ibm.com/products/spss-statistics (cit. on p. 73).

IBM. (2020). *SPSS Statistics* (Version 27.0.X.X) [Computer software]. https://ibm.com/products/spss-statistics (cit. on pp. 143, 198).

IJsselsteijn, W. A., de Kort, Y. A. W., & Haans, A. (2006). Is this my hand I see before me? The rubber hand illusion in reality, virtual reality, and mixed reality. *Presence: Teleoperators & Virtual Environments*, *15*(4), 455–464. https://doi.org/10.1162/pres.15.4.455 (cit. on pp. 10, 98, 126).

Inoue, Y., & Kitazaki, M. (2021). Virtual mirror and beyond: The psychological basis for avatar embodiment via a mirror. *Journal of Robotics and Mechatronics*, *33*(5), 1004–1012. https://doi.org/10.20965/jrm.2021.p1004 (cit. on pp. 10, 22, 29, 31, 123, 126, 127, 148, 149).

Irvine, K. R., McCarty, K., McKenzie, K. J., Pollet, T. V., Cornelissen, K. K., Tovée, M. J., & Cornelissen, P. L. (2019). Distorted body image influences body schema in individuals with negative bodily attitudes. *Neuropsychologia*, *122*, 38–50. https://doi.org/10.1016/j.neuropsychologia.2018.11.015 (cit. on pp. 31, 38, 150).

International Organization for Standardization. (2019). *Ergonomics of human-system interaction – Part 210: Human-centred design for interactive systems* (Standard). ISO/TC 159/SC 4 Ergonomics of human-system interaction. https://www.iso.org/standard/77520.html (cit. on pp. 2, 57).

Jamieson, S. (2004). Likert scales: How to (ab)use them. *Medical Education*, *38*(12), 1217–1218. https://doi.org/10.1111/j.1365-2929.2004.02012.x (cit. on p. 50).

Jiang, J., Streli, P., Qiu, H., Fender, A., Laich, L., Snape, P., & Holz, C. (2022). AvatarPoser: Articulated full-body pose tracking from sparse motion sensing. *Computer Vision – ECCV 2022*, 443–460. https://doi.org/0.1007/978-3-031-20065-6_26 (cit. on pp. 42, 51).

Johnstone, A. M., Stewart, A. D., Benson, P. J., Kalafati, M., Rectenwald, L., & Horgan, G. (2008). Assessment of body image in obesity using a digital morphing technique. *Journal of Human Nutrition and Dietetics*, *21*(3), 256–267. https://doi.org/10.1111/j.1365-277X.2008.00862.x (cit. on p. 56).

Jung, M., Kim, J., & Kim, K. (2020). Measuring recognition of body changes over time: A human-computer interaction tool using dynamic morphing and body ownership illusion. *PLOS ONE*, *15*(9), 1–14. https://doi.org/10.1371/journal.pone.0239322 (cit. on p. 188).

Jung, S., & Hughes, C. E. (2016). The effects of indirect real body cues of irrelevant parts on virtual body ownership and presence. *Proceedings of the 26th International Conference on Artificial Reality and Telexistence and the 21st Eurographics Symposium on Virtual Environments*, 107–114. 10.5555/3061323.3061345 (cit. on pp. 10, 24, 28, 29, 47, 98, 101).

Kadleček, P., Ichim, A.-E., Liu, T., Křivánek, J., & Kavan, L. (2016). Reconstructing personalized anatomical models for physics-based body animation. *ACM Trans. Graph.*, *35*(6). https://doi.org/10.1145/2980179.2982438 (cit. on pp. 43, 51).

Kalckert, A., & Ehrsson, H. H. (2012). Moving a rubber hand that feels like your own: A dissociation of ownership and agency. *Frontiers in Human Neuroscience*, *6*, 40. https://doi.org/10.3389/fnhum.2012.00040 (cit. on pp. 69, 106, 167).

Kalus, A., Kocur, M., Klein, J., Mayer, M., & Henze, N. (2023). PumpVR: Rendering the weight of objects and avatars through liquid mass transfer in virtual reality. *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems*. https://doi.org/10.1145/3544548.3581172 (cit. on p. 51).

Kamaria, K., Vikram, M., & Ayiesah, R. (2016). Body image perception, body shape concern and body shape dissatisfaction among undergraduates students. *Jurnal Teknologi*, *78*(6–8). https://doi.org/10.11113/jt.v78.9050 (cit. on pp. 8, 16, 31, 38, 135, 150).

Kaplan, R. A., Rossell, S. L., Enticott, P. G., & Castle, D. J. (2013). Own-body perception in body dysmorphic disorder. *Cognitive Neuropsychiatry*, *18*(6), 594–614. https://doi.org/10.1080/13546805.2012.758878 (cit. on p. 8).

Keizer, A., van Elburg, A., Helms, R., & Dijkerman, H. C. (2016). A virtual reality full body illusion improves body image disturbance in anorexia nervosa. *PLOS ONE*, *11*(10). https://doi.org/10.1371/journal.pone.0163921 (cit. on pp. 27, 56, 97, 100, 101, 116).

Kelly, J. W. (2022). Distance perception in virtual reality: A meta-analysis of the effect of head-mounted display characteristics. *IEEE Transactions on Visualization and Computer Graphics*, 1–13. https://doi.org/10.1109/TVCG.2022.3196606 (cit. on pp. 19, 29, 31, 40, 124, 125, 148, 152).

Kelly, J. W., Cherep, L. A., Klesel, B., Siegel, Z. D., & George, S. (2018). Comparison of two methods for improving distance perception in virtual reality. *ACM Transactions on Applied Perception (TAP)*, *15*(2). https://doi.org/10.1145/3165285 (cit. on pp. 23, 125, 150).

Kelly, J. W., Doty, T. A., Ambourn, M., & Cherep, L. A. (2022). Distance perception in the Oculus Quest and Oculus Quest 2. *Frontiers in Virtual Reality*, *3*. https://doi.org/10.3389/frvir.2022.850471 (cit. on pp. 31, 148).

Kenealy, P., Gleeson, K., Frude, N., & Shaw, W. (1991). The importance of the individual in the "causal" relationship between attractiveness and self-esteem. *Journal of Community & Applied Social Psychology*, *1*(1), 45–56. https://doi.org/10.1002/casp.2450010108 (cit. on pp. 17, 38, 151).

Kennedy, R. S., Lane, N. E., Berbaum, K. S., & Lilienthal, M. G. (1993). Simulator sickness questionnaire: An enhanced method for quantifying simulator sickness. *The International Journal of Aviation Psychology*, *3*(3), 203–220. https://doi.org/10.1207/s15327108ijap0303_3 (cit. on pp. 57, 69, 106, 135, 167, 192).

Khalsa, S. S., Portnoff, L. C., McCurdy-McKinnon, D., & Feusner, J. D. (2017). What happens after treatment? A systematic review of relapse, remission, and recovery in anorexia nervosa. *Journal of Eating Disorders*, *5*(20), 1–12. https://doi.org/10.1186/s40337-017-0145-3 (cit. on p. 8).

Kilteni, K., Bergstrom, I., & Slater, M. (2013). Drumming in immersive virtual reality: The body shapes the way we play. *IEEE Transactions on Visualization and Computer Graphics*, *19*(4), 597–605. https://doi.org/10.1109/TVCG.2013.29 (cit. on pp. 12, 126).

Kilteni, K., Groten, R., & Slater, M. (2012). The sense of embodiment in virtual reality. *Presence: Teleoperators & Virtual Environments*, *21*(4), 373–387. https://doi.org/10.1162/PRES_a_00124 (cit. on pp. 10, 23, 31, 58, 69, 98, 101, 123, 126, 127, 148, 149, 160).

Klevjer, R. (2012). Enter the avatar: The phenomenology of prosthetic telepresence in computer games. In J. R. Sageng, H. Fossheim, & T. Mandt Larsen (Eds.), *The philosophy of computer games* (pp. 17–38). Springer Netherlands. https://doi.org/10.1007/978-94-007-4249-9_3 (cit. on p. 10).

Kocur, M., Kalus, A., Bogon, J., Henze, N., Wolff, C., & Schwind, V. (2022). The rubber hand illusion in virtual reality and the real world – Comparable but different. *Proceedings of the 28th ACM Symposium on Virtual Reality Software and Technology*. https://doi.org/10.1145/3562939.3565614 (cit. on p. 10).

Kocur, M., Kloss, M., Schwind, V., Wolff, C., & Henze, N. (2020). Flexing muscles in virtual reality: Effects of avatars' muscular appearance on physical performance. *Proceedings of the Annual Symposium on Computer-Human Interaction in Play*, 193–205. https://doi.org/10.1145/3410404.3414261 (cit. on p. 11).

Komaritzan, M., Wenninger, S., & Botsch, M. (2021). Inside humans: Creating a simple layered anatomical model from human surface scans. *Frontiers in Virtual Reality*, *2*. https://doi.org/10.3389/frvir.2021.694244 (cit. on p. 87).

Kreimeier, J., Hammer, S., Friedmann, D., Karg, P., Bühner, C., Bankel, L., & Götzelmann, T. (2019). Evaluation of different types of haptic feedback influencing the task-based presence and performance in virtual reality. *Proceedings of the 12th ACM International Conference on Pervasive Technologies Related to Assistive Environments*, 289–298. https://doi.org/10.1145/3316782.3321536 (cit. on p. 2).

Krijn, M., Emmelkamp, P. M., Biemond, R., de Wilde de Ligny, C., Schuemie, M. J., & van der Mast, C. A. (2004). Treatment of acrophobia in virtual reality: The role of immersion and presence. *Behaviour Research and Therapy*, *42*(2), 229–239. https://doi.org/10.1016/S0005-7967(03)00139-6 (cit. on pp. 3, 98, 160).

Krumpal, I. (2013). Determinants of social desirability bias in sensitive surveys: A literature review. *Quality & Quantity*, *47*(4), 2025–2047 (cit. on p. 50).

Latoschik, M. E., Kern, F., Stauffert, J.-P., Bartl, A., Botsch, M., & Lugrin, J.-L. (2019). Not alone here?! Scalability and user experience of embodied ambient crowds in distributed social virtual reality. *IEEE Transactions on Visualization and Computer Graphics*, *25*(5), 2134–2144. https://doi.org/10.1109/TVCG.2019.2899250 (cit. on p. 48).

Latoschik, M. E., Lugrin, J.-L., & Roth, D. (2016). FakeMi: A fake mirror system for avatar embodiment studies. *Proceedings of the 22nd ACM Conference on Virtual Reality Software and Technology*, 73–76. https://doi.org/10.1145/2993369.2993399 (cit. on pp. 33, 176).

Latoschik, M. E., & Wienrich, C. (2022). Congruence and plausibility, not presence: Pivotal conditions for XR experiences and effects, a novel approach. *Frontiers in Virtual Reality*, *3*. https://doi.org/10.3389/frvir.2022.694433 (cit. on pp. 1, 5, 8, 11, 15, 17, 20, 21, 33–35, 46, 47, 50, 61, 127, 129, 174, 175, 185, 187, 188, 202, 203).

LaViola, J. J., Kruijff, E., McMahan, R. P., Bowman, D., & Poupyrev, I. P. (2017). *3D user interfaces: Theory and practice*. Addison-Wesley Professional. https://www.oreilly.com/library/view/3d-user-interfaces/9780134034478/ (cit. on pp. 2, 59, 65).

Lessiter, J., Freeman, J., Keogh, E., & Davidoff, J. (2001). A cross-media presence questionnaire: The ITC-sense of presence inventory. *Presence: Teleoperators and Virtual Environments*, *10*(3), 282–297. https://doi.org/10.1162/105474601300343612 (cit. on pp. 178, 191).

Leyrer, M., Linkenauger, S. A., Bülthoff, H. H., Kloos, U., & Mohler, B. (2011). The influence of eye height and avatars on egocentric distance estimates in immersive virtual environments. *Proceedings of the ACM SIGGRAPH Symposium on Applied Perception in Graphics and Visualization*, 67–74. https://doi.org/10.1145/2077451.2077464 (cit. on pp. 10, 31, 125, 148, 153).

Likert, R. (1932). A technique for the measurement of attitudes. *Archives of psychology* (cit. on p. 50).

LimeSurvey GmbH. (2019). *Limesurvey* (Version 3) [Computer software]. https://limesurvey.org (cit. on p. 108).

LimeSurvey GmbH. (2020). *Limesurvey* (Version 4) [Computer software]. https://limesurvey.org (cit. on pp. 132, 168, 193).

Lin, J., Cronjé, J., Käthner, I., Pauli, P., & Latoschik, M. E. (2023). Measuring interpersonal trust towards virtual humans with a virtual maze paradigm. *IEEE Transactions on Visualization and Computer Graphics*, 1–11. https://doi.org/10.1109/TVCG.2023.3247095 (cit. on p. 14).

Lin, J.-W., Duh, H., Parker, D., Abi-Rached, H., & Furness, T. (2002). Effects of field of view on presence, enjoyment, memory, and simulator sickness in a virtual environment. *Proceedings IEEE Virtual Reality 2002*, 164–171. https://doi.org/10.1109/VR.2002.996519 (cit. on p. 2).

Longo, M. R. (2017). Distorted body representations in healthy cognition. *Quarterly Journal of Experimental Psychology*, *70*(3), 378–388. https://doi.org/10.1080/17470218.2016.1143956 (cit. on pp. 85, 96).

Loomis, J., & Knapp, J. (2003). Visual perception of egocentric distance in real and virtual environments. In L. J. Hettinger & M. W. Haas (Eds.), *Virtual and adaptive environments* (pp. 21–46). Lawrence Erlbaum Associates Publishers. https://doi.org/10.1201/9781410608888 (cit. on pp. 40, 125).

Lugrin, J.-L., Ertl, M., Krop, P., Klüpfel, R., Stierstorfer, S., Weisz, B., Rück, M., Schmitt, J., Schmidt, N., & Latoschik, M. E. (2018). Any "body" there? Avatar visibility effects in a virtual reality game. *2018 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, 17–24. https://doi.org/10.1109/VR.2018.8446229 (cit. on pp. 7, 98, 101, 184).

Lugrin, J.-L., Latoschik, M. E., Habel, M., Roth, D., Seufert, C., & Grafe, S. (2016). Breaking bad behaviors: A new tool for learning classroom management using virtual reality. *Frontiers in ICT*, *3*. https://doi.org/10.3389/fict.2016.00026 (cit. on pp. 7, 184).

Lugrin, J.-L., Latt, J., & Latoschik, M. E. (2015). Anthropomorphism and illusion of virtual body ownership. *Proceedings of the 25th International Conference on Artificial Reality and Telexistence and 20th Eurographics Symposium on Virtual Environments*, 1–8. https://dl.acm.org/doi/abs/10.5555/2852313.2852314 (cit. on pp. 21, 129, 185, 189).

Ma, F., & Pan, X. (2022). Visual fidelity effects on expressive self-avatar in virtual reality: First impressions matter. *2022 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, 57–65. https://doi.org/10.1109/VR51125.2022.00023 (cit. on p. 15).

Maalin, N., Mohamed, S., Kramer, R. S., Cornelissen, P. L., Martin, D., & Tovée, M. J. (2020). Beyond BMI for self-estimates of body size and shape: A new method for developing stimuli correctly calibrated for body composition. *Behavior Research Methods*, *53*, 1–14. https://doi.org/10.3758/s13428-020-01494-1 (cit. on pp. 9, 27, 43, 51, 55–57, 84).

Mal, D., Döllinger, N., Wolf, E., Wenninger, S., Botsch, M., Wienrich, C., & Latoschik, M. E. (2024a). Am I the odd one? Exploring (in)congruencies in the realism of avatars and virtual others in virtual reality. *Frontiers in Virtual Reality*, *5*. https://doi.org/10.3389/frvir.2024.1417066 (cit. on pp. 49, 249).

Mal, D., Wolf, E., Döllinger, N., Botsch, M., Wienrich, C., & Latoschik, M. E. (2022). Virtual human coherence and plausibility – Towards a validated scale. *2022 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW)*, 788–789. https://doi.org/10.1109/VRW55335.2022.00245 (cit. on pp. 6, 8, 17, 20, 47, 49, 50, 187, 192, 203, 248).

Mal, D., Wolf, E., Döllinger, N., Botsch, M., Wienrich, C., & Latoschik, M. E. (2024b). From 2D-screens to VR: Exploring the effect of immersion on the plausibility of virtual humans, 1–8. https://doi.org/10.1145/3613905.3650773 (cit. on pp. 8, 49, 249).

Mal, D., Wolf, E., Döllinger, N., Wienrich, C., & Latoschik, M. E. (2023). The impact of avatar and environment congruence on plausibility, embodiment, presence, and the proteus effect. *IEEE Transactions on Visualization and Computer Graphics*, 1–11. https://doi.org/10.1109/TVCG.2023.3247089 (cit. on pp. 6, 11, 12, 20, 48, 126, 248).

Matamala-Gomez, M., Diaz Gonzalez, A. M., Slater, M., & Sanchez-Vives, M. V. (2019). Decreasing pain ratings in chronic arm pain through changing a virtual body: Different strategies for different pain types. *The Journal of Pain*, *20*(6), 685–697. https://doi.org/10.1016/j.jpain.2018.12.001 (cit. on p. 11).

Matamala-Gomez, M., Maselli, A., Malighetti, C., Realdon, O., Mantovani, F., & Riva, G. (2021). Virtual body ownership illusions for mental health: A narrative review. *Journal of Clinical Medicine*, *10*(1), 139. https://doi.org/10.3390/jcm10010139 (cit. on pp. 7, 9, 12, 13, 123, 158, 177, 184).

Maximova, K., McGrath, J. J., Barnett, T., O'Loughlin, J., Paradis, G., & Lambert, M. (2008). Do you see what I see? Weight status misperception and exposure to obesity among children and adolescents. *International Journal of Obesity*, *32*(6), 1008. https://doi.org/10.1038/ijo.2008.15 (cit. on pp. 15, 56, 96).

Meadows, A., & Calogero, R. M. (2018). Studies on weight stigma and body image in higher-weight individuals. In *Body image, eating, and weight* (pp. 381–400). Springer. https://doi.org/10.1007/978-3-319-90817-5_28 (cit. on pp. 54, 56).

Menzel, T., Botsch, M., & Latoschik, M. E. (2022). Automated blendshape personalization for faithful face animations using commodity smartphones. *Proceedings of the 28th ACM Symposium on Virtual Reality Software and Technology*. https://doi.org/10.1145/3562939.3565622 (cit. on p. 51).

Menzel, T., Wolf, E., Wenninger, S., Spinczyk, N., Holderrieth, L., Schwanecke, U., Latoschik, M. E., & Botsch, M. (2024). Wildavatars: Smartphone-based reconstruction of full-body avatars in the wild. *TechRxiv*. https://doi.org/10.36227/techrxiv.172503940.07538627/v1 (cit. on p. 250).

Meta. (2022). *Meta Quest Pro*. https://www.meta.com/quest/quest-pro (cit. on p. 51).

Microsoft. (2019a). *HoloLens 2*. https://microsoft.com/hololens (cit. on pp. 32, 34, 38, 39, 45, 159, 162, 187, 193).

Microsoft. (2019b). *Mixed Reality Toolkit (MRTK)* (Version 2) [Computer software]. https://learn.microsoft.com/windows/mixed-reality/mrtk-unity/mrtk2 (cit. on pp. 32, 48).

Milgram, P., & Kishino, F. (1994). A taxonomy of mixed reality visual displays. *IEICE Transactions on Information and Systems*, *77*(12), 1321–1329. https://www.researchgate.net/publication/231514051_a_taxonomy_of_mixed_reality_visual_displays (cit. on p. 2).

Milgram, P., Takemura, H., Utsumi, A., & Kishino, F. (1995). Augmented reality: A class of displays on the reality-virtuality continuum. *Telemanipulator and Telepresence Technologies*, *2351*, 282–293. https://doi.org/10.1117/12.197321 (cit. on pp. 160, 186).

Miro. (2021). *Miro Board*. https://miro.com/ (cit. on p. 172).

Mohler, B. J., Creem-Regehr, S. H., Thompson, W. B., & Bülthoff, H. H. (2010). The effect of viewing a self-avatar on distance judgments in an HMD-based virtual environment. *Presence*, *19*(3), 230–242. https://doi.org/10.1162/pres.19.3.230 (cit. on pp. 10, 31, 125, 128, 148, 153).

Mölbert, S. C., Thaler, A., Streuber, S., Black, M. J., Karnath, H.-O., Zipfel, S., Mohler, B., & Giel, K. E. (2017a). Investigating body image disturbance in anorexia nervosa using novel biometric figure rating scales: A pilot study. *European Eating Disorders Review*, *25*(6), 607–612. https://doi.org/10.1002/erv.2559 (cit. on p. 44).

Mölbert, S. C., Klein, L., Thaler, A., Mohler, B. J., Brozzo, C., Martus, P., Karnath, H.-O., Zipfel, S., & Giel, K. E. (2017b). Depictive and metric body size estimation in anorexia nervosa and bulimia nervosa: A systematic review and meta-analysis. *Clinical Psychology Review*, *57*, 21–31. https://doi.org/10.1016/j.cpr.2017.08.005 (cit. on pp. 15, 96).

Mölbert, S. C., Thaler, A., Mohler, B. J., Streuber, S., Romero, J., Black, M. J., Zipfel, S., Karnath, H.-O., & Giel, K. E. (2018). Assessing body image in anorexia nervosa using biometric self-avatars in virtual reality: Attitudinal components rather than visual body size estimation are distorted. *Psychological Medicine*, *48*(4), 642–653. https://doi.org/10.1017/S0033291717002008 (cit. on pp. 9, 101, 123, 128, 129).

Mori, M. (1970). Bukimi no tani [the uncanny valley]. *Energy*, *7*, 33–35. https://spectrum.ieee.org/the-uncanny-valley (cit. on pp. 21, 129, 189).

Mori, M., MacDorman, K. F., & Kageki, N. (2012). The uncanny valley [from the field]. *IEEE Robotics Automation Magazine*, *19*(2), 98–100. https://doi.org/10.1109/MRA.2012.2192811 (cit. on pp. 21, 129, 185, 189).

Mottelson, A., Muresan, A., Hornbæk, K., & Makransky, G. (2023). A systematic review and meta-analysis of the effectiveness of body ownership illusions in virtual reality. *ACM Trans. Comput.-Hum. Interact.* https://doi.org/10.1145/3590767 (cit. on pp. 11, 22, 45).

Müller, M., Bender, J., Chentanez, N., & Macklin, M. (2016). A robust method to extract the rotational part of deformations. *Proceedings of the 9th International Conference on Motion in Games*, 55–60. https://doi.org/10.1145/2994258.2994269 (cit. on pp. 30, 48, 61, 137).

Mystakidis, S. (2022). Metaverse. *Encyclopedia*, *2*(1), 486–497. https://doi.org/10.3390/encyclopedia2010031 (cit. on p. 8).

NaturalPoint. (2018). *OptiTrack Flex 3*. https://optitrack.com/cameras/flex-3/ (cit. on p. 42).

Neyret, S., Bellido Rivas, A. I., Navarro, X., & Slater, M. (2020a). Which body would you like to have? The impact of embodied perspective on body perception and body evaluation in immersive virtual reality. *Frontiers in Robotics and AI*, *7*, 31. https://doi.org/10.3389/frobt.2020.00031 (cit. on pp. 8, 23, 43, 45, 56, 97, 99, 101, 116, 123, 128, 141, 188).

Neyret, S., Navarro, X., Beacco, A., Oliva, R., Bourdin, P., Valenzuela, J., Barberia, I., & Slater, M. (2020b). An embodied perspective as a victim of sexual harassment in virtual reality reduces action conformity in a later milgram obedience scenario. *Scientific Reports*, *10*(1), 6207. https://doi.org/10.1038/s41598-020-62932-w (cit. on p. 8).

Niehorster, D. C., Li, L., & Lappe, M. (2017). The accuracy and precision of position and orientation tracking in the HTC Vive virtual reality system for scientific research. *i-Perception*, *8*(3), 2041669517708205. https://doi.org/10.1177/2041669517708205 (cit. on pp. 62, 136).

Nimcharoen, C., Zollmann, S., Collins, J., & Regenbrecht, H. (2018). Is that me? – Embodiment and body perception with an augmented reality mirror. *2018 IEEE International Symposium on Mixed and Augmented Reality Adjunct (ISMAR-Adjunct)*, 158–163. https://doi.org/10.1109/ISMAR-Adjunct.2018.00057 (cit. on pp. 18, 57, 99, 101, 161).

Normand, J.-M., Giannopoulos, E., Spanlang, B., & Slater, M. (2011). Multisensory stimulation can induce an illusion of larger belly size in immersive virtual reality. *PLOS ONE*, *6*(1), e16128. https://doi.org/10.1371/journal.pone.0016128 (cit. on pp. 12, 27, 56, 98, 100, 116).

Nowak, K. L., & Fox, J. (2018). Avatars and computer-mediated communication: A review of the definitions, uses, and effects of digital representations. *Review of Communication Research*, *6*, 30–53. https://doi.org/10.12840/issn.2255-4165.2018.06.01.015 (cit. on p. 6).

O'Connor, S. (2019). Virtual reality and avatars in health care. *Clinical Nursing Research*, *28*(5), 523–528. https://doi.org/10.1177/1054773819845824 (cit. on pp. 7, 184).

O'Dea, J. (2012). Body image and self-esteem. In T. Cash (Ed.), *Encyclopedia of body image and human appearance* (pp. 141–147). Academic Press. https://doi.org/10.1016/B978-0-12-384925-0.00021-3 (cit. on pp. 8, 16, 31, 38, 135, 150).

Oreshkin, B. N., Bocquelet, F., Harvey, F. G., Raitt, B., & Laflamme, D. (2022). ProtoRes: Proto-residual network for pose authoring via learned inverse kinematics. *International Conference on Learning Representations*. https://openreview.net/forum?id=s03aqxehtd_ (cit. on p. 51).

Paeratakul, S., White, M. A., Williamson, D. A., Ryan, D. H., & Bray, G. A. (2002). Sex, race/ethnicity, socioeconomic status, and BMI in relation to self-perception of overweight. *Obesity Research*, *10*(5), 345–350. https://doi.org/10.1038/oby.2002.48 (cit. on pp. 15, 104, 204).

Park, B., Cho, H. N., Choi, E., Seo, D. H., Kim, S., Park, Y.-R., Choi, K. S., & Rhee, Y. (2019). Self-perceptions of body weight status according to age-groups among korean women: A nationwide population-based survey. *PLOS ONE*, *14*(1), 1–15. https://doi.org/10.1371/journal.pone.0210486 (cit. on p. 15).

Park, J. (2018). Emotional reactions to the 3D virtual body and future willingness: The effects of self-esteem and social physique anxiety. *Virtual Reality*, *22*(1), 1–11. https://doi.org/10.1007/s10055-017-0314-3 (cit. on p. 17).

Pastel, S., Chen, C.-H., Petri, K., & Witte, K. (2020). Effects of body visualization on performance in head-mounted display virtual reality. *PLOS ONE*, *15*(9), 1–18. https://doi.org/10.1371/journal.pone.0239226 (cit. on p. 10).

Patzer, G. L. (1995). Self-esteem and physical attractiveness. *Journal of Esthetic and Restorative Dentistry*, *7*(6), 274–276. https://doi.org/10.1080/00223980.1975.9923921 (cit. on pp. 17, 38, 151).

Pearse, N. (2011). Deciding on the scale granularity of response categories of likert type scales: The case of a 21-point scale. *Electronic Journal of Business Research Methods*, *9*(2), 159–171. https://academic-publishing.org/index.php/ejbrm/article/view/1278 (cit. on p. 50).

Peat, C. M., & Muehlenkamp, J. J. (2011). Self-objectification, disordered eating, and depression: A test of mediational pathways. *Psychology of Women Quarterly*, *35*(3), 441–450. https://doi.org/10.1177/036168431140038 (cit. on p. 56).

Peck, T. C., & Gonzalez-Franco, M. (2021). Avatar embodiment. A standardized questionnaire. *Frontiers in Virtual Reality*, *1*. https://doi.org/10.3389/frvir.2020.575943 (cit. on p. 126).

Peck, T. C., Good, J. J., Erickson, A., Bynum, I., & Bruder, G. (2022). Effects of transparency on perceived humanness: Implications for rendering skin tones using optical see-through displays. *IEEE Transactions on Visualization and Computer Graphics*, *28*(5), 2179–2189. https://doi.org/10.1109/TVCG.2022.3150521 (cit. on p. 19).

Peck, T. C., Seinfeld, S., Aglioti, S. M., & Slater, M. (2013). Putting yourself in the skin of a black avatar reduces implicit racial bias. *Consciousness and Cognition*, *22*(3), 779–787. https://doi.org/10.1016/j.concog.2013.04.016 (cit. on p. 11).

Peña, J., Hancock, J. T., & Merola, N. A. (2009). The priming effects of avatars in virtual settings. *Communication Research*, *36*(6), 838–856. https://doi.org/10.1177/0093650209346802 (cit. on p. 116).

Philbeck, J. W., & Loomis, J. M. (1997). Comparison of two indicators of perceived egocentric distance under full-cue and reduced-cue conditions. *Journal of Experimental Psychology: Human Perception and Performance*, *23*(1), 72–85. https://doi.org/10.1037/0096-1523.23.1.72 (cit. on pp. 30, 135).

Piryankova, I. V., Stefanucci, J. K., Romero, J., De La Rosa, S., Black, M. J., & Mohler, B. J. (2014a). Can I recognize my body's weight? The influence of shape and texture on the perception of self. *ACM Transactions on Applied Perception (TAP)*, *11*(3), 13:1–13:18. https://doi.org/10.1145/2641568 (cit. on pp. 9, 18, 21, 26, 42, 55, 57, 63, 70, 87, 97, 99, 101, 116, 128, 188, 195).

Piryankova, I. V., Wong, H. Y., Linkenauger, S. A., Stinson, C., Longo, M. R., Bülthoff, H. H., & Mohler, B. J. (2014b). Owning an overweight or underweight body: Distinguishing the physical, experienced and virtual body. *PLOS ONE*, *9*(8), e103428. https://doi.org/10.1371/journal.pone.0103428 (cit. on pp. 12, 27, 56, 84, 98, 100, 116).

Pook, M., Tuschen-Caffier, B., & Stich, N. (2002). Evaluation des fragebogens zum figurbewusstsein (FFB, Deutsche version des body shape questionnaire). *Verhaltenstherapie*, *12*(2), 116–124. https://doi.org/10.1159/000064375 (cit. on pp. 106, 135, 167).

Portingale, J., Krug, I., Liu, H., Kiropoulos, L., & Butler, D. (2024). Your body, my experience: A systematic review of embodiment illusions as a function of and method to improve body image disturbance. *Clinical Psychology: Science and Practice*, 1–15. https://doi.org/10.1037/cps0000223 (cit. on p. 9).

Praetorius, A. S., & Görlich, D. (2020). How avatars influence user behavior: A review on the Proteus effect in virtual environments and video games. *International Conference on the Foundations of Digital Games*, 1–9. https://doi.org/10.1145/3402942.3403019 (cit. on p. 12).

Preston, C., & Ehrsson, H. H. (2018). Implicit and explicit changes in body satisfaction evoked by body size illusions: Implications for eating disorder vulnerability in women. *PLOS ONE*, *13*(6), e0199426. https://doi.org/10.1371/journal.pone.0199426 (cit. on p. 56).

Pujades, S., Mohler, B., Thaler, A., Tesch, J., Mahmood, N., Hesse, N., Bülthoff, H. H., & Black, M. J. (2019). The virtual caliper: Rapid creation of metrically accurate avatars from 3D measurements. *IEEE Transactions on Visualization and Computer Graphics*, *25*(5), 1887–1897. https://doi.org/10.1109/TVCG.2019.2898748 (cit. on pp. 8, 27, 41, 43, 51, 83, 84).

Putze, S., Alexandrovsky, D., Putze, F., Höffner, S., Smeddinck, J. D., & Malaka, R. (2020). Breaking the experience: Effects of questionnaires in VR user studies. *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*, 1–15. https://doi.org/0.1145/3313831.3376144 (cit. on p. 72).

R Core Team. (2020). *R: A language and environment for statistical computing* (Version 4.0.5) [Computer software]. https://r-project.org (cit. on pp. 73, 109, 169).

Ranasinghe, N., Jain, P., Karwita, S., Tolley, D., & Do, E. Y.-L. (2017). Ambiotherm: Enhancing sense of presence in virtual reality by simulating real-world environmental conditions. *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*, 1731–1742. https://doi.org/10.1145/3025453.3025723 (cit. on p. 2).

Ratan, R., Beyea, D., Li, B. J., & Graciano, L. (2020). Avatar characteristics induce users' behavioral conformity with small-to-medium effect sizes: A meta-analysis of the proteus effect. *Media Psychology*, *23*(5), 651–675. https://doi.org/10.1080/15213269.2019.1623698 (cit. on pp. 12, 55, 116, 123–125, 158, 161).

Renner, R. S., Velichkovsky, B. M., & Helmert, J. R. (2013). The perception of egocentric distances in virtual environments – A review. *ACM Computing Surveys*, *46*(2). https://doi.org/10.1145/2543581.2543590 (cit. on pp. 29, 124, 125, 128, 153).

Ries, B., Interrante, V., Kaeding, M., & Anderson, L. (2008). The effect of self-embodiment on distance perception in immersive virtual environments. *Proceedings of the 2008 ACM Symposium on Virtual Reality Software and Technology*, 167–170. https://doi.org/10.1145/1450579.1450614 (cit. on pp. 10, 125, 153).

Riva, G. (1997). The virtual environment for body-image modification (VEBIM): Development and preliminary evaluation. *Presence: Teleoperators and Virtual Environments*, *6*(1), 106–117. https://doi.org/10.1162/pres.1997.6.1.106 (cit. on p. 56).

Riva, G., Gutiérrez-Maldonado, J., Dakanalis, A., & Ferrer-García, M. (2019). Virtual reality in the assessment and treatment of weight-related disorders. In *Virtual reality for psychological and neurocognitive interventions* (pp. 163–193). Springer New York. https://doi.org/10.1007/978-1-4939-9482-3_7 (cit. on pp. 9, 55, 56, 58, 82, 159).

Robinette, K. M., Blackwell, S., Daanen, H., Boehmer, M., & Fleming, S. (2002). *Civilian american and european surface anthropometry resource (CEASAR)* (tech. rep.). Sytronics. https://doi.org/10.21236/ada406704 (cit. on pp. 63, 139, 194).

Rolland, J. P., & Fuchs, H. (2000). Optical versus video see-through head-mounted displays in medical visualization. *Presence: Teleoperators and Virtual Environments*, *9*(3), 287–309. https://doi.org/10.1162/105474600566808 (cit. on p. 161).

Romano, D., Pfeiffer, C., Maravita, A., & Blanke, O. (2014). Illusory self-identification with an avatar reduces arousal responses to painful stimuli. *Behavioural Brain Research*, *261*, 275–281. https://doi.org/10.1016/j.bbr.2013.12.049 (cit. on p. 133).

Rosen, J. C. (2001). Improving body image in obesity. In *Body image, eating disorders, and obesity: An integrative guide for assessment and treatment* (pp. 425–440). American Psychological Association. https://doi.org/10.1037/10502-017 (cit. on pp. 54, 56).

Rosenberg, M. (2015). *Society and the adolescent self-image*. Princeton University Press. https://www.jstor.org/stable/j.ctt183pjjh (cit. on pp. 106, 135, 167).

Roth, D., & Latoschik, M. E. (2020). Construction of the virtual embodiment questionnaire (VEQ). *IEEE Transactions on Visualization and Computer Graphics*, *26*(12), 3546–3556. https://doi.org/10.1109/TVCG.2020.3023603 (cit. on pp. 50, 69, 101, 106, 126, 133, 160, 167).

Roth, D., & Wienrich, C. (2018). Effects of media immersiveness on the perception of virtual characters. *15th Workshop on Virtual and Augmented Reality of the GI Special Interest Group VR/AR*. https://www.researchgate.net/publication/327344504_effects_of_media_immersiveness_on_the_perception_of_virtual_characters (cit. on pp. 18, 185, 189, 196).

Roth, M., Decker, O., Herzberg, P. Y., & Brähler, E. (2008). Dimensionality and norms of the Rosenberg self-esteem scale in a german general population sample. *European Journal of Psychological Assessment*, *24*(3), 190–197. https://doi.org/10.1027/1015-5759.24.3.190 (cit. on pp. 106, 135, 167).

Rothbaum, B. O. (2006). *Pathological anxiety: Emotional processing in etiology and treatment*. Guilford Press. https://psycnet.apa.org/record/2005-16244-000 (cit. on pp. 3, 160).

Sagnier, C., Loup-Escande, E., & Valléry, G. (2020). Effects of gender and prior experience in immersive user experience with virtual reality. *Advances in Usability and User Experience. AHFE 2019. Advances in Intelligent Systems and Computing*, 305–314. https://doi.org/10.1007/978-3-030-19135-1_30 (cit. on p. 17).

Salagean, A., Crellin, E., Parsons, M., Cosker, D., & Stanton Fraser, D. (2023). Meeting your virtual twin: Effects of photorealism and personalization on embodiment, self-identification and perception of self-avatars in virtual reality. *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems*. https://doi.org/10.1145/3544548.3581182 (cit. on pp. 15, 21, 41).

Sampaio, M., Navarro Haro, M. V., De Sousa, B., Vieira Melo, W., & Hoffman, H. G. (2021). Therapists make the switch to telepsychology to safely continue treating their patients during the COVID-19 pandemic. Virtual reality telepsychology may be next. *Frontiers in Virtual Reality*, *1*. https://doi.org/10.3389/frvir.2020.576421 (cit. on p. 8).

Scavarelli, A., Arya, A., & Teather, R. J. (2021). Virtual reality and augmented reality in social learning spaces: A literature review. *Virtual Reality*, *25*(1), 257–277. https://doi.org/10.1007/s10055-020-00444-8 (cit. on pp. 7, 184).

Schopenhauer, A. (1904). Aphorisms for life wisdom (cit. on p. 1).

Schubert, T., Friedmann, F., & Regenbrecht, H. (2001). The experience of presence: Factor analytic insights. *Presence: Teleoperators & Virtual Environments*, *10*(3), 266–281. https://doi.org/10.1162/105474601300343603 (cit. on pp. 50, 69, 105, 167).

Schwartz, M. B., & Brownell, K. D. (2004). Obesity and body image. *Body Image*, *1*(1), 43–56. https://doi.org/10.1016/S1740-1445(03)00007-X (cit. on p. 106).

Schwind, V., Knierim, P., Haas, N., & Henze, N. (2019). Using presence questionnaires in virtual reality. *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*, 1–12. https://doi.org/10.1145/3290605.3300590 (cit. on p. 117).

Sedgwick, H. A. (1986). Space perception. In K. R. Boff, L. Kaufman, & J. P. Thomas (Eds.), *Handbook of perception and human performance* (pp. 21.1–21.57, Vol. 1). Wiley New York. https://psycnet.apa.org/record/1986-98619-000 (cit. on p. 124).

Skarbez, R., Frederick P. Brooks, J., & Whitton, M. C. (2017). A survey of presence and related concepts. *ACM Computing Surveys*, *50*(6), 96. https://doi.org/10.1145/3134301 (cit. on pp. 3, 4, 34, 98, 165, 186).

Skarbez, R., Gabbard, J., Bowman, D. A., Ogle, T., & Tucker, T. (2021a). Virtual replicas of real places: Experimental investigations. *IEEE Transactions on Visualization and Computer Graphics*, 1–1. https://doi.org/10.1109/TVCG.2021.3096494 (cit. on pp. 187, 193).

Skarbez, R., Smith, M., & Whitton, M. C. (2021b). Revisiting milgram and kishino's reality-virtuality continuum. *Frontiers in Virtual Reality*, *2*. https://doi.org/10.3389/frvir.2021.647997 (cit. on pp. 1, 3, 4, 33–35, 47, 50, 185–187, 203).

Škola, F., & Liarokapis, F. (2016). Examining the effect of body ownership in immersive virtual and augmented reality environments. *The Visual Computer*, *32*(6), 761–770. https://doi.org/10.1007/s00371-016-1246-8 (cit. on pp. 19, 160, 161, 165).

Slater, M. (2004). How colorful was your day? Why questionnaires cannot assess presence in virtual environments. *Presence: Teleoperators & Virtual Environments*, *13*(4), 484–493. https://doi.org/10.1162/1054746041944849 (cit. on p. 117).

Slater, M. (2009). Place illusion and plausibility can lead to realistic behaviour in immersive virtual environments. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *364*(1535), 3549–3557. https://doi.org/10.1098/rstb.2009.0138 (cit. on pp. 2, 3, 34, 57, 61, 98, 160, 186).

Slater, M. (2018). Immersion and the illusion of presence in virtual reality. *British Journal of Psychology*, *109*(3), 431–433. https://doi.org/10/ggdd3s (cit. on p. 160).

Slater, M., Pérez Marcos, D., Ehrsson, H., & Sanchez-Vives, M. V. (2009). Inducing illusory ownership of a virtual body. *Frontiers in Neuroscience*, *3*. https://doi.org/10.3389/neuro.01.029.2009 (cit. on pp. 10, 58, 126).

Slater, M., Spanlang, B., & Corominas, D. (2010a). Simulating virtual environments within virtual environments as the basis for a psychophysics of presence. *ACM Transactions on Graphics (TOG)*, *29*(4), 1–9. https://doi.org/10.1145/1778765.1778829 (cit. on pp. 98, 101).

Slater, M., Spanlang, B., Sanchez-Vives, M. V., & Blanke, O. (2010b). First person experience of body transfer in virtual reality. *PLOS ONE*, *5*(5), e10564. https://doi.org/10.1371/journal.pone.0010564 (cit. on pp. 10, 58, 98, 122, 126, 140).

Slater, M., & Wilbur, S. (1997). A framework for immersive virtual environments (FIVE): Speculations on the role of presence in virtual environments. *Presence: Teleoperators & Virtual Environments*, *6*(6), 603–616. https://doi.org/10.1162/pres.1997.6.6.603 (cit. on pp. 2, 3, 160).

Soares, I., B. Sousa, R., Petry, M., & Moreira, A. P. (2021). Accuracy and repeatability tests on HoloLens 2 and HTC Vive. *Multimodal Technologies and Interaction*, *5*(8). https://doi.org/10.3390/mti5080047 (cit. on p. 163).

Song, M.-H., & Godøy, R. I. (2016). How fast is your body motion? Determining a sufficient frame rate for an optical motion tracking system using passive markers. *PLOS ONE*, *11*(3), 1–14. https://doi.org/10.1371/journal.pone.0150993 (cit. on p. 20).

Sorkine, O. (2005). Laplacian Mesh Processing. *Eurographics 2005 - State of the Art Reports*, 53–70. https://doi.org/10.2312/egst.20051044 (cit. on p. 64).

Spanlang, B., Normand, J.-M., Borland, D., Kilteni, K., Giannopoulos, E., Pomés, A., González-Franco, M., Perez-Marcos, D., Arroyo-Palacios, J., Muncunill, X. N., & Slater, M. (2014). How to build an embodiment lab: Achieving body representation illusions in virtual reality. *Frontiers in Robotics and AI*, *1*, 9. https://doi.org/10.3389/frobt.2014.00009 (cit. on pp. 10, 22, 126).

Speicher, M., Hall, B. D., & Nebeling, M. (2019). What is mixed reality? *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*, 1–15. https://doi.org/10.1145/3290605.3300767 (cit. on p. 3).

Spitzley, K. A., & Karduna, A. R. (2019). Feasibility of using a fully immersive virtual reality system for kinematic data collection. *Journal of Biomechanics*, *87*, 172–176. https://doi.org/10.1016/j.jbiomech.2019.02.015 (cit. on p. 138).

Spreckelsen, P. v., Glashouwer, K. A., Bennik, E. C., Wessel, I., & de Jong, P. J. (2018). Negative body image: Relationships with heightened disgust propensity, disgust sensitivity, and self-directed disgust. *PLOS ONE*, *13*(6), 1–15. https://doi.org/10.1371/journal.pone.0198532 (cit. on p. 8).

Stanney, K. M., Kennedy, R. S., & Drexler, J. M. (1997). Cybersickness is not simulator sickness. *Proceedings of the Human Factors and Ergonomics Society annual meeting*, *41*, 1138–1142. https://doi.org/10.1177/107118139704100292 (cit. on pp. 69, 74, 136, 192, 202).

Statistisches Bundesamt. (2021). *Körpermaße nach Altersgruppen und Geschlecht*. https://www.destatis.de/de/themen/gesellschaft-umwelt/gesundheit/gesundheitszustand-relevantes-verhalten/tabellen/liste-koerpermasse.html (cit. on p. 37).

Stauffert, J.-P., Korwisi, K., Niebling, F., & Latoschik, M. E. (2021). Ka-Boom!!! Visually exploring latency measurements for XR. In *Extended abstracts of the 2021 CHI conference on human factors in computing systems* (pp. 1–9). Association for Computing Machinery. https://doi.org/10.1145/3411763.3450379 (cit. on pp. 60, 136, 193).

Stauffert, J.-P., Niebling, F., & Latoschik, M. E. (2018). Effects of latency jitter on simulator sickness in a search task. *2018 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, 121–127. https://doi.org/10.1109/VR.2018.8446195 (cit. on pp. 20, 69, 135, 192).

Stauffert, J.-P., Niebling, F., & Latoschik, M. E. (2020). Latency and cybersickness: Impact, causes, and measures. A review. *Frontiers in Virtual Reality*, *1*. https://doi.org/10.3389/frvir.2020.582204 (cit. on pp. 20, 69, 135, 136, 192, 193).

Steed, A., Pan, Y., Zisch, F., & Steptoe, W. (2016). The impact of a self-avatar on cognitive load in immersive virtual reality. *2016 IEEE Virtual Reality (VR)*, 67–76. https://doi.org/10.1109/VR.2016.7504689 (cit. on p. 10).

Stefan, N., Birkenfeld, A. L., & Schulze, M. B. (2021). Global pandemics interconnected – Obesity, impaired metabolic health and COVID-19. *Nature Reviews Endocrinology*, *17*(3), 135–149. https://doi.org/10.1038/s41574-020-00462-1 (cit. on p. 54).

Stefanucci, J. K., & Geuss, M. N. (2009). Big people, little world: The body influences size perception. *Perception*, *38*(12), 1782–1795. https://doi.org/10.1068/p6437 (cit. on p. 128).

Stoll, C., Hasler, N., Gall, J., Seidel, H.-P., & Theobalt, C. (2011). Fast articulated motion tracking using a sums of gaussians body model. *2011 International Conference on Computer Vision*, 951–958. https://doi.org/10.1109/ICCV.2011.6126338 (cit. on pp. 32, 42, 48, 159, 162).

Sutherland, I. E. (1968). A head-mounted three-dimensional display. *Proceedings of the December 9-11, 1968, Fall Joint Computer Conference, Part I*, 757–764. https://doi.org/10.1145/1476589.1476686 (cit. on pp. 3, 98).

Tanaka, K., Nakanishi, H., & Ishiguro, H. (2015). Physical embodiment can produce robot operator's pseudo presence. *Frontiers in ICT*, *2*, 8. https://doi.org/10.3389/fict.2015.00008 (cit. on pp. 98, 101).

Tanay, G., & Bernstein, A. (2013). State mindfulness scale (SMS): Development and initial validation. *Psychological assessment*, *25*(4), 1286. https://doi.org/10.1037/a0034044 (cit. on p. 70).

Tang, X., Sun, W., Yang, Y.-L., & Jin, X. (2021). Parametric reshaping of portraits in videos. *Proceedings of the 29th ACM International Conference on Multimedia*, 4689–4697. https://doi.org/10.1145/3474085.3475334 (cit. on pp. 55, 56, 87).

Tcha-Tokey, K., Loup-Escande, E., Christmann, O., & Richir, S. (2016). A questionnaire to measure the user experience in immersive virtual environments. *Proceedings of the 2016 Virtual Reality International Conference*, 1–5. https://doi.org/10.1145/2927929.2927955 (cit. on pp. 2, 57).

Thaler, A. (2019). *The role of visual cues in body size estimation* [Doctoral dissertation]. Logos Verlag Berlin GmbH. (Cit. on pp. 13, 55, 56, 96, 128, 141, 153, 188).

Thaler, A., Geuss, M. N., Mölbert, S. C., Giel, K. E., Streuber, S., Romero, J., Black, M. J., & Mohler, B. J. (2018a). Body size estimation of self and others in females varying in BMI. *PLOS ONE*, *13*(2), e0192152. https://doi.org/10.1371/journal.pone.0192152 (cit. on pp. 9, 14–16, 18, 21, 23, 27–29, 37, 43, 56, 57, 70, 83, 85, 97, 99–101, 115, 128, 176, 178, 185, 188).

Thaler, A., Piryankova, I. V., Stefanucci, J. K., Pujades, S., de la Rosa, S., Streuber, S., Romero, J., Black, M. J., & Mohler, B. J. (2018b). Visual perception and evaluation of photo-realistic self-avatars from 3D body scans in males and females. *Frontiers in ICT*, *5*, 18. https://doi.org/10.3389/fict.2018.00018 (cit. on pp. 9, 15, 18, 70, 99, 101, 128, 188, 204).

Thaler, A., Pujades, S., Stefanucci, J. K., Creem-Regehr, S. H., Tesch, J., Black, M. J., & Mohler, B. J. (2019). The influence of visual perspective on body size estimation in immersive virtual reality. *ACM Symposium on Applied Perception 2019*, 1–12. https://doi.org/10.1145/3343036.3343134 (cit. on pp. 8, 18, 23, 45, 97, 99, 101, 123, 128, 133, 141, 188, 191).

Thompson, J. K., & Tantleff-Dunn, S. (1998). MINI-REVIEW Assessment of body image disturbance in obesity. *Obesity Research*, *6*(5), 375–377. https://doi.org/10.1002/j.1550-8528.1998.tb00366.x (cit. on pp. 8, 54).

Thompson, J. C., Trafton, J. G., & McKnight, P. (2011). The perception of humanness from the movements of synthetic agents. *Perception*, *40*(6), 695–704. https://doi.org/10.1068/p6900 (cit. on p. 20).

Tian, N., Lopes, P., & Boulic, R. (2022). A review of cybersickness in head-mounted displays: Raising attention to individual susceptibility. *Virtual Reality*, *26*(4), 1409–1441. https://doi.org/10.1145/3448304 (cit. on p. 17).

Todd, J., Aspell, J. E., Barron, D., & Swami, V. (2019a). An exploration of the associations between facets of interoceptive awareness and body image in adolescents. *Body image*, *31*, 171–180. https://doi.org/10.1016/j.bodyim.2019.10.004 (cit. on p. 56).

Todd, J., Aspell, J. E., Barron, D., & Swami, V. (2019b). Multiple dimensions of interoceptive awareness are associated with facets of body image in british adults. *Body Image*, *29*, 6–16. https://doi.org/10.1016/j.bodyim.2019.02.003 (cit. on pp. 54, 56).

Tourangeau, R., & Rasinski, K. A. (1988). Cognitive processes underlying context effects in attitude measurement. *Psychological Bulletin*, *103*(3), 299 (cit. on p. 50).

Tsakiris, M. (2008). Looking for myself: Current multisensory input alters self-face recognition. *PLOS ONE*, *3*(12), 1–6. https://doi.org/10.1371/journal.pone.0004040 (cit. on pp. 22, 127, 149).

Tsakiris, M., & Haggard, P. (2005). The rubber hand illusion revisited: Visuotactile integration and self-attribution. *Journal of Experimental Psychology: Human Perception and Performance*, *31*(1), 80. https://doi.org/10.1037/0096-1523.31.1.80 (cit. on pp. 10, 98).

Tseng, W.-J., Bonnail, E., McGill, M., Khamis, M., Lecolinet, E., Huron, S., & Gugenheimer, J. (2022). The dark side of perceptual manipulations in virtual reality. *Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems*. https://doi.org/10.1145/3491102.3517728 (cit. on p. 44).

Turbyne, C., Goedhart, A., de Koning, P., Schirmbeck, F., & Denys, D. (2021). Systematic review and meta-analysis of virtual reality in mental healthcare: Effects of full body illusions on body image disturbance. *Frontiers in Virtual Reality*, *2*, 39. https://doi.org/10.3389/frvir.2021.657638 (cit. on pp. 9, 12, 13, 21, 34, 54–56, 58, 82, 123, 125, 129, 159, 177, 184, 188).

Tuschen-Caffier, B., Bender, C., Caffier, D., Klenner, K., Braks, K., & Svaldi, J. (2015). Selective visual attention during mirror exposure in anorexia and bulimia nervosa. *PLOS ONE*, *10*(12), e0145886. https://doi.org/10.1371/journal.pone.0145886 (cit. on pp. 38, 151).

Unity Technologies. (2019). *Unity* (Version 2019.4.X LTS) [Computer software]. https://unity.com/releases/2019-lts (cit. on pp. 60, 102, 136).

Unity Technologies. (2020). *Unity* (Version 2020.3.X LTS) [Computer software]. https://unity.com/releases/2020-lts (cit. on pp. 2, 162, 193).

Valtolina, G. G. (1998). Body-size estimation by obese subjects. *Perceptual and Motor Skills*, *86*(3), 1363–1374. https://doi.org/10.2466/pms.1998.86.3c.1363 (cit. on pp. 15, 56).

Valve. (2020a). *Half-life: Alyx* [Computer software]. https://half-life.com/alyx (cit. on pp. 7, 184).

Valve. (2020b). *SteamVR* (Version 1.13.9) [Computer software]. https://store.steampowered.com/app/250820/SteamVR (cit. on p. 102).

Valve. (2020c). *Valve Index*. https://store.steampowered.com/valveindex (cit. on pp. 39, 49, 60, 136).

Valve. (2021). *SteamVR* (Version 1.16.10) [Computer software]. https://store.steampowered.com/app/250820/SteamVR (cit. on pp. 26, 47, 60, 136).

Varjo. (2021a). *Varjo Base* (Version 3) [Computer software]. https://varjo.com/use-center/get-to-know-your-headset/using-varjo-base/ (cit. on pp. 34, 48).

Varjo. (2021b). *Varjo XR-3*. https://varjo.com/products/xr-3 (cit. on pp. 34, 39, 187, 193).

Venegas, O., & Mehrzad, R. (2020). Chapter 3 – Prevalence and trends in obesity in the united states and affluent countries. In *Obesity* (pp. 19–41). Elsevier. https://doi.org/10.1016/B978-0-12-818839-2.00003-X (cit. on p. 54).

Voges, M. M., Giabbiconi, C.-M., Schöne, B., Waldorf, M., Hartmann, A. S., & Vocks, S. (2019). Double standards in body evaluation? The influence of identification with body stimuli on ratings of attractiveness, body fat, and muscle mass. *Eating and Weight Disorders - Studies on Anorexia, Bulimia and Obesity*, *24*(6), 1173–1180. https://doi.org/10.1007/s40519-017-0450-5 (cit. on p. 37).

Voges, M. M., Quittkat, H. L., Schöne, B., & Vocks, S. (2022). Giving a body a different face – How men and women evaluate their own body vs. that of others. *Frontiers in Psychology*, *13*. https://doi.org/10.3389/fpsyg.2022.853398 (cit. on p. 37).

Vox, J. P., Weber, A., Wolf, K. I., Izdebski, K., Schüler, T., König, P., Wallhoff, F., & Friemert, D. (2021). An evaluation of motion trackers with virtual reality sensor technology in comparison to a marker-based motion capture system based on joint angles for ergonomic risk assessment. *Sensors*, *21*(9). https://doi.org/10.3390/s21093145 (cit. on p. 138).

Walker, D. C., White, E. K., & Srinivasan, V. J. (2018). A meta-analysis of the relationships between body checking, body image avoidance, body image dissatisfaction, mood, and disordered eating. *International Journal of Eating Disorders*, *51*(8), 745–770. https://doi.org/10.1002/eat.22867 (cit. on p. 56).

Waltemate, T., Gall, D., Roth, D., Botsch, M., & Latoschik, M. E. (2018). The impact of avatar personalization and immersion on virtual body ownership, presence, and emotional response. *IEEE Transactions on Visualization and Computer Graphics*, *24*(4), 1643–1652. https://doi.org/10.1109/TVCG.2018.2794629 (cit. on pp. 3, 10, 15, 19, 21, 27–29, 33, 34, 42, 69, 82, 106, 127, 149, 160, 165, 167, 174, 177, 185, 196, 205).

Waltemate, T., Senna, I., Hülsmann, F., Rohde, M., Kopp, S., Ernst, M., & Botsch, M. (2016). The impact of latency on perceptual judgments and motor performance in closed-loop interaction in virtual reality. *Proceedings of the 22nd ACM Symposium on Virtual Reality Software and Technology*, 27–35. https://doi.org/10.1145/2993369.2993381 (cit. on pp. 19, 20, 60, 137, 176).

Wang, K., Iwai, D., & Sato, K. (2017). Supporting trembling hand typing using optical see-through mixed reality. *IEEE Access*, *5*, 10700–10708. https://doi.org/10.1109/ACCESS.2017.2711058 (cit. on pp. 19, 161).

Wanous, J. P., & Hudy, M. J. (2001). Single-item reliability: A replication and extension. *Organizational Research Methods*, *4*(4), 361–375. https://doi.org/10.1177/109442810144003 (cit. on p. 117).

Ware, C., Arthur, K., & Booth, K. S. (1993). Fish tank virtual reality. *Proceedings of the INTERACT '93 and CHI '93 Conference on Human Factors in Computing Systems*, 37–42. https://doi.org/10.1145/169059.169066 (cit. on p. 3).

Weidner, F., Boettcher, G., Arboleda, S. A., Diao, C., Sinani, L., Kunert, C., Gerhardt, C., Broll, W., & Raake, A. (2023a). A systematic review on the visualization of avatars and agents in AR & VR displayed using head-mounted displays. *IEEE Transactions on Visualization and Computer Graphics*, 1–11. https://doi.org/10.1109/TVCG.2023.3247072 (cit. on pp. 21, 41).

Weidner, F., Maier, J. E., & Broll, W. (2023b). Eating, smelling, and seeing: Investigating multisensory integration and (in)congruent stimuli while eating in VR. *IEEE Transactions on Visualization and Computer Graphics*, 1–11. https://doi.org/10.1109/TVCG.2023.3247099 (cit. on pp. 2, 20).

Welch, R. B., Blackmon, T. T., Liu, A., Mellers, B. A., & Stark, L. W. (1996). The effects of pictorial realism, delay of visual feedback, and observer interactivity on the subjective sense of presence. *Presence: Teleoperators and Virtual Environments*, *5*(3), 263–273. https://doi.org/10.1162/pres.1996.5.3.263 (cit. on p. 2).

Wenninger, S., Achenbach, J., Bartl, A., Latoschik, M. E., & Botsch, M. (2020). Realistic virtual humans from smartphone videos. *26th ACM Symposium on Virtual Reality Software and Technology*, 1–11. https://doi.org/10.1145/3385956.3418940 (cit. on pp. 8, 27, 55, 81, 86).

Westermeier, F., Brübach, L., Latoschik, M. E., & Wienrich, C. (2023). Exploring plausibility and presence in mixed reality experiences. *IEEE Transactions on Visualization and Computer Graphics*, 1–10. https://doi.org/10.1109/TVCG.2023.3247046 (cit. on p. 6).

Wiederhold, B. K., Riva, G., & Gutiérrez-Maldonado, J. (2016). Virtual reality in the assessment and treatment of weight-related disorders. *Cyberpsychology, Behavior, and Social Networking*, *19*(2), 67–73. https://doi.org/10.1089/cyber.2016.0012 (cit. on p. 55).

Wienrich, C., Döllinger, N., & Hein, R. (2021a). Behavioral framework of immersive technologies (BehaveFIT): How and why virtual reality can support behavioral change processes. *Frontiers in Virtual Reality*, *2*, 84. https://doi.org/10.3389/frvir.2021.627194 (cit. on pp. 3, 11, 21, 31, 34, 55, 56, 129, 158–160, 184, 187).

Wienrich, C., Döllinger, N., Kock, S., & Gramann, K. (2019). User-centered extension of a locomotion typology: Movement-related sensory feedback and spatial learning. *2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, 690–698. https://doi.org/10.1109/VR.2019.8798070 (cit. on p. 125).

Wienrich, C., & Gramlich, J. (2020). AppRaiseVR – An evaluation framework for immersive experiences. *i-com*, *19*(2), 103–121. https://doi.org/10.1515/icom-2020-0008 (cit. on pp. 2, 55, 57, 58).

Wienrich, C., Komma, P., Vogt, S., & Latoschik, M. E. (2021b). Spatial presence in mixed realities – Considerations about the concept, measures, design, and experiments. *Frontiers in Virtual Reality*, *2*, 141. https://doi.org/10.3389/frvir.2021.694315 (cit. on pp. 18, 19, 34, 160, 185, 187, 203).

Willemsen, P., & Gooch, A. (2002). Perceived egocentric distances in real, image-based, and traditional virtual environments. *Proceedings IEEE Virtual Reality 2002*, 275–276. https://doi.org/10.1109/VR.2002.996536 (cit. on p. 125).

Williams, A. S., Garcia, J., & Ortega, F. (2020). Understanding multimodal user gesture and speech behavior for object manipulation in augmented reality using elicitation. *IEEE Transactions on Visualization and Computer Graphics*, *26*(12), 3479–3489. https://doi.org/10.1109/TVCG.2020.3023566 (cit. on p. 59).

Witmer, B. G., & Singer, M. J. (1998). Measuring presence in virtual environments: A presence questionnaire. *Presence: Teleoperators and Virtual Environments*, *7*(3), 225–240. https://doi.org/10.1162/105474698565686 (cit. on p. 17).

Wolf, E., Döllinger, N., Mal, D., Wenninger, S., Andrea, B., Botsch, M., Latoschik, M. E., & Wienrich, C. (2022a). Does distance matter? Embodiment and perception of personalized avatars in relation to the self-observation distance in virtual reality. *Frontiers in Virtual Reality*, *3*. https://doi.org/10.3389/frvir.2022.1031093 (cit. on pp. 25, 121).

Wolf, E., Döllinger, N., Mal, D., Wienrich, C., Botsch, M., & Latoschik, M. E. (2020). Body weight perception of females using photorealistic avatars in virtual and augmented reality. *2020 IEEE International Symposium on Mixed and Augmented Reality (ISMAR)*, 583–594. https://doi.org/10.1109/ISMAR50242.2020.00071 (cit. on pp. 11, 13, 16, 18–20, 23, 26–28, 31–34, 37, 38, 42, 43, 46, 48, 55–57, 70, 72, 82, 85, 97, 99–105, 114–116, 123, 128, 138, 141, 159, 161, 164–167, 174–177, 185, 188, 192, 194, 196, 202, 247).

Wolf, E., Fiedler, M. L., Döllinger, N., Wienrich, C., & Latoschik, M. E. (2022b). Exploring presence, avatar embodiment, and body perception with a holographic augmented reality mirror. *2022 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, 350–359. https://doi.org/10.1109/VR51125.2022.00054 (cit. on pp. 25, 55, 57, 70, 82, 86, 123, 128, 138, 141, 148, 153, 157, 185, 189, 192, 196, 203).

Wolf, E., Klüber, S., Zimmerer, C., Lugrin, J.-L., & Latoschik, M. E. (2019). "Paint that object yellow": Multimodal interaction to enhance creativity during design tasks in VR. *2019 International Conference on Multimodal Interaction*, 195–204. https://doi.org/10.1145/3340555.3353724 (cit. on p. 247).

Wolf, E., Mal, D., Frohnapfel, V., Döllinger, N., Wenninger, S., Botsch, M., Latoschik, M. E., & Wienrich, C. (2022c). Plausibility and perception of personalized virtual humans between virtual and augmented reality. *2022 IEEE International Symposium on Mixed and Augmented Reality (ISMAR)*, 489–498. https://doi.org/10.1109/ISMAR55827.2022.00065 (cit. on pp. 25, 57, 123, 128, 129, 134, 141, 148, 150, 153, 183).

Wolf, E., Merdan, N., Döllinger, N., Mal, D., Wienrich, C., Botsch, M., & Latoschik, M. E. (2021). The embodiment of photorealistic avatars influences female body weight perception in virtual reality. *2021 IEEE Virtual Reality and 3D User Interfaces (VR)*, 65–74. https://doi.org/10.1109/VR50410.2021.00027 (cit. on pp. 24, 55–57, 70, 95, 123, 141, 151, 161, 176, 188, 192, 204).

Wolf, E., Wienrich, C., & Latoschik, M. E. (2024). Towards an altered body image through the exposure to a modulated self in virtual reality. *2024 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW)*, 857–858. https://doi.org/10.1109/VRW62533.2024.00225 (cit. on p. 249).

World Health Organization. (2000). *Obesity: Preventing and managing the global epidemic: Report of a WHO consultation*. https://apps.who.int/iris/handle/10665/42330 (cit. on pp. 14, 57).

World Health Organization. (2016). *Obesity and overweight*. https://www.who.int/news-room/fact-sheets/detail/obesity-and-overweight (cit. on p. 54).

World Health Organization. (2019). *International statistical classification of diseases and related health problems (11th ed.)* https://icd.who.int/ (cit. on pp. 54, 56, 123, 167).

Wu, H., Luo, W., Pan, N., Nan, S., Deng, Y., Fu, S., & Yang, L. (2019). Understanding freehand gestures: A study of freehand gestural interaction for immersive VR shopping applications. *Human-centric Computing and Information Sciences*, *9*(1), 1–26. https://doi.org/10.1186/s13673-019-0204-7 (cit. on p. 59).

Wu, T. L., Gomes, A., Fernandes, K., & Wang, D. (2019). The effect of head tracking on the degree of presence in virtual reality. *International Journal of Human–Computer Interaction*, *35*(17), 1569–1577. https://doi.org/10.1080/10447318.2018.1555736 (cit. on p. 2).

Xiao, Q., Tang, X., Wu, Y., Jin, L., Yang, Y.-L., & Jin, X. (2020). Deep shapely portraits. *Proceedings of the 28th ACM International Conference on Multimedia*, 1800–1808. https://doi.org/10.1145/3394171.3413873 (cit. on pp. 55, 56, 63, 87).

Yee, N., & Bailenson, J. (2007). The Proteus effect: The effect of transformed self-representation on behavior [Publisher: Oxford Academic]. *Human Communication Research*, *33*(3), 271–290. https://doi.org/10.1111/j.1468-2958.2007.00299.x (cit. on pp. 8, 11, 55, 116, 123, 158).

Yee, N., Bailenson, J. N., & Ducheneaut, N. (2009). The Proteus effect: Implications of transformed digital self-representation on online and offline behavior. *Communication Research*, *36*(2), 285–312. https://doi.org/10.1177/0093650208330254 (cit. on pp. 8, 11, 98, 116).

Yun, H., Ponton, J. L., Andujar, C., & Pelechano, N. (2023). Animation fidelity in self-avatars: Impact on user performance and sense of agency. *2023 IEEE Conference Virtual Reality and 3D User Interfaces (VR)*, 286–296. https://doi.org/10.1109/VR55154.2023.00044 (cit. on p. 20).

Zanetti, T., Santonastaso, P., Sgaravatti, E., Degortes, D., & Favaro, A. (2013). Clinical and temperamental correlates of body image disturbance in eating disorders. *European Eating Disorders Review*, *21*(1), 32–37. https://doi.org/10.1002/erv.2190 (cit. on p. 56).

Zell, E., Aliaga, C., Jarabo, A., Zibrek, K., Gutierrez, D., McDonnell, R., & Botsch, M. (2015). To stylize or not to stylize? The effect of shape and material stylization on the perception of computer-generated faces. *ACM Trans. Graph.*, *34*(6). https://doi.org/10.1145/2816795.2818126 (cit. on p. 41).

Zhao, H., Jin, X., Huang, X., Chai, M., & Zhou, K. (2018). Parametric reshaping of portrait images for weight-change. *IEEE computer graphics and applications*, *38*(1), 77–90. https://doi.org/10.1109/MCG.2018.011461529 (cit. on pp. 55, 56, 87).

Zhou, S., Fu, H., Liu, L., Cohen-Or, D., & Han, X. (2010). Parametric reshaping of human bodies in images. *ACM Trans. Graph.*, *29*(4). https://doi.org/10.1145/1778765.1778863 (cit. on pp. 55, 56).

Zijlstra, F. R. H. (1993). *Efficiency in work behaviour: A design approach for modern tools* [Doctoral dissertation, Delft University]. http://resolver.tudelft.nl/uuid:d97a028b-c3dc-4930-b2ab-a7877993a17f (cit. on pp. 69, 134).

Zimmerer, C., Wolf, E., Wolf, S., Fischbach, M., Lugrin, J.-L., & Latoschik, M. E. (2020). Finally on par?! Multimodal and unimodal interaction for open creative design tasks in virtual reality. *Proceedings of the 2020 International Conference on Multimodal Interaction*, 222–231. https://doi.org/10.1145/3382507.3418850 (cit. on p. 247).

Ziser, K., Mölbert, S. C., Stuber, F., Giel, K. E., Zipfel, S., & Junne, F. (2018). Effectiveness of body image directed interventions in patients with anorexia nervosa: A systematic review. *International Journal of Eating Disorders*, *51*(10), 1121–1127. https://doi.org/10.1002/eat.22946 (cit. on p. 56).

Appendices

List of Achievements

Publications

In addition to the already listed published works that represent direct contributions to the presented dissertation, further work has been carried out in the same period that either did not contribute at all or only indirectly to the dissertation. The following list contains publications that I have been authoring or coauthoring besides the dissertation in ascending chronological order.

1. Döllinger, N., Wienrich, C., Wolf, E., & Latoschik, M. E. (2019). ViTraS – Virtual reality therapy by stimulation of modulated body image – Project outline. *Mensch und Computer 2019 – Workshopband*, 1–6. https://doi.org/10.18420/muc2019-ws-633
2. Wolf, E., Klüber, S., Zimmerer, C., Lugrin, J.-L., & Latoschik, M. E. (2019). "Paint that object yellow": Multimodal interaction to enhance creativity during design tasks in VR. *2019 International Conference on Multimodal Interaction*, 195–204. https://doi.org/10.1145/3340555.3353724
3. Zimmerer, C., Wolf, E., Wolf, S., Fischbach, M., Lugrin, J.-L., & Latoschik, M. E. (2020). Finally on par?! Multimodal and unimodal interaction for open creative design tasks in virtual reality. *Proceedings of the 2020 International Conference on Multimodal Interaction*, 222–231. https://doi.org/10.1145/3382507.3418850
4. Wolf, E., Döllinger, N., Mal, D., Wienrich, C., Botsch, M., & Latoschik, M. E. (2020). Body weight perception of females using photorealistic avatars in virtual and augmented reality. *2020 IEEE International Symposium on Mixed and Augmented Reality (ISMAR)*, 583–594. https://doi.org/10.1109/ISMAR50242.2020.00071
5. Bartl, A., Jung, S., Kullmann, P., Wenninger, S., Achenbach, J., Wolf, E., Schell, C., Lindeman, R. W., Botsch, M., & Latoschik, M. E. (2021a). Self-avatars in virtual reality: A study protocol for investigating the impact of the deliberateness of choice and the

context-match. *2021 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW)*, 565–566. https://doi.org/10.1109/VRW52623.2021.00165

6. Bartl, A., Wenninger, S., Wolf, E., Botsch, M., & Latoschik, M. E. (2021b). Affordable but not cheap: A case study of the effects of two 3D-reconstruction methods of virtual humans. *Frontiers in Virtual Reality*, *2*. https://doi.org/10.3389/frvir.2021.694617

7. Mal, D., Wolf, E., Döllinger, N., Botsch, M., Wienrich, C., & Latoschik, M. E. (2022). Virtual human coherence and plausibility – Towards a validated scale. *2022 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW)*, 788–789. https://doi.org/10.1109/VRW55335.2022.00245

8. Döllinger, N., Wolf, E., Mal, D., Erdmannsdörfer, N., Botsch, M., Latoschik, M. E., & Wienrich, C. (2022b). Virtual reality for mind and body: Does the sense of embodiment towards a virtual body affect physical body awareness? *Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems*, 1–8. https://doi.org/10.1145/3491101.3519613

9. Döllinger, N., Göttfert, C., Wolf, E., Mal, D., Latoschik, M. E., & Wienrich, C. (2022a). Analyzing eye tracking data in mirror exposure. *Proceedings of the Conference on Mensch und Computer*, *Proceedings of Mensch Und Computer 2022*, 513–517. https://doi.org/10.1145/3543758.3547567

10. Mal, D., Wolf, E., Döllinger, N., Wienrich, C., & Latoschik, M. E. (2023). The impact of avatar and environment congruence on plausibility, embodiment, presence, and the proteus effect. *IEEE Transactions on Visualization and Computer Graphics*, 1–11. https://doi.org/10.1109/TVCG.2023.3247089

11. Fiedler, M. L., Wolf, E., Döllinger, N., Botsch, M., Latoschik, M. E., & Wienrich, C. (2023a). Embodiment and personalization for self-identification with virtual humans. *2023 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW)*, 799–800. https://doi.org/10.1109/VRW58643.2023.00242

12. Döllinger, N., Wolf, E., Botsch, M., Latoschik, M. E., & Wienrich, C. (2023b). Are embodied avatars harmful to our self-experience? The impact of virtual embodiment on body awareness. *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems*. https://doi.org/10.1145/3544548.3580918

13. Fiedler, M. L., Wolf, E., Wienrich, C., & Latoschik, M. E. (2023b). Holographic augmented reality mirrors for daily self-reflection on the own body image. *Integrating Individual and Social Contexts into Self-Reflection Technologies Workshop (WS28, CHI '23)*. https://downloads.hci.informatik.uni-wuerzburg.de/2023-chi-reflection-workshop.pdf

14. Mal, D., Wolf, E., Döllinger, N., Botsch, M., Wienrich, C., & Latoschik, M. E. (2024b). From 2D-screens to VR: Exploring the effect of immersion on the plausibility of virtual humans, 1–8. https://doi.org/10.1145/3613905.3650773

15. Döllinger, N., Beck, M., Wolf, E., Mal, D., Botsch, M., Latoschik, M. E., & Wienrich, C. (2023a). "If it's not me it doesn't make a difference" – The impact of avatar customization and personalization on user experience and body awareness in virtual reality. *2023 IEEE International Symposium on Mixed and Augmented Reality (ISMAR)*. https://doi.org/10.1109/ISMAR59233.2023.00063

16. Gemesi, K., Döllinger, N., Weinberger, N.-A., Erik, W., Mal, D., Wienrich, C., Luck-Sikorski, C., Bader, E., & Holzapfel, C. (2023). Auswirkung von (virtuellen) Körperbildübungen auf das Ernährungsverhalten von Personen mit Adipositas – Ergebnisse der ViTraS-Pilotstudie. *Adipositas - Ursachen, Folgeerkrankungen, Therapie*, *17*(03), S10–05. https://doi.org/10.1055/s-0043-1771568

17. Wolf, E., Wienrich, C., & Latoschik, M. E. (2024). Towards an altered body image through the exposure to a modulated self in virtual reality. *2024 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW)*, 857–858. https://doi.org/10.1109/VRW62533.2024.00225

18. Mal, D., Döllinger, N., Wolf, E., Wenninger, S., Botsch, M., Wienrich, C., & Latoschik, M. E. (2024a). Am I the odd one? Exploring (in)congruencies in the realism of avatars and virtual others in virtual reality. *Frontiers in Virtual Reality*, *5*. https://doi.org/10.3389/frvir.2024.1417066

19. Döllinger, N., Mal, D., Keppler, S., Wolf, E., Botsch, M., Israel, J. H., Latoschik, M. E., & Wienrich, C. (2024a). Virtual body swapping: A VR-based approach to embodied third-person self-processing in mind-body therapy, 1–18. https://doi.org/10.1145/3613904.3642328

20. Fiedler, M. L., Wolf, E., Döllinger, N., Mal, D., Botsch, M., Latoschik, M. E., & Wienrich, C. (2024). From avatars to agents: Self-related cues through embodiment and personalization affect body perception in virtual reality. *IEEE Transactions on Visualization and Computer Graphics*, 1–11. https://doi.org/10.1109/TVCG.2024.3456211

21. Döllinger, N., Mal, D., Sinn, M., Wolf, E., Wienrich, C., & Latoschik, M. E. (2024b). The effect of delay on virtual body ownership and body awareness [Manuscript in preparation for publication]

22. Menzel, T., Wolf, E., Wenninger, S., Spinczyk, N., Holderrieth, L., Schwanecke, U., Latoschik, M. E., & Botsch, M. (2024). Wildavatars: Smartphone-based reconstruction of full-body avatars in the wild. *TechRxiv*. https://doi.org/10.36227/techrxiv.172503940.07538627/v1

Dissemination

During the period of my dissertation, I actively participated in the following national and international symposia, meetings, or conferences listed in ascending chronological order for the purpose of scientific dissemination.

1. Technical Demonstration @ 2019 Places VR Festival, Gelsenkirchen, Germany
2. Workshop Participation @ 2019 ACM Conference on Mensch und Computer (MuC), Hamburg, Germany
3. Oral Presentation @ 2019 ACM International Conference on Multimodal Interaction (ICMI), Suzhou, China
4. Oral Presentation @ 2020 IEEE International Symposium on Mixed and Augmented Reality (ISMAR), Online
5. Oral Presentation @ 2021 IEEE Conference on Virtual Reality and 3D User Interfaces (VR), Online
6. Poster Presentation @ 2022 ACM Conference on Human Factors in Computing Systems (CHI), New Orleans, USA
7. Oral Presentation @ 2022 IEEE Conference on Virtual Reality and 3D User Interfaces (VR), Online
8. Oral Presentation @ 2022 IEEE International Symposium on Mixed and Augmented Reality (ISMAR), Online
9. Technical Demonstration @ 2023 Würtual Reality XR Meeting, Würzburg, Germany
10. Poster Presentation @ 2023 ACM Conference on Human Factors in Computing Systems (CHI), Hamburg, Germany
11. Participation @ 2023 IEEE International Symposium on Mixed and Augmented Reality (ISMAR), Sydney, Australia

12. Poster Presentation @ 2024 IEEE Conference on Virtual Reality and 3D User Interfaces (VR), Orlando, Florida, USA

Awards

The work carried out during the period of my dissertation has received the following awards, which are listed in ascending chronological order.

1. The research project ViTraS received the award for the "Best Impact" at DIVR Science Award 2019.
2. The paper "Paint that object yellow: Multimodal Interaction to Enhance Creativity During Design Tasks in VR" received the Best Paper Runner-Up at ICMI 2019.
3. The paper "Finally on Par?! Multimodal and Unimodal Interaction for Open Creative Design Tasks in Virtual Reality" has been Best Paper Nominee at ICMI 2020.
4. I received the prestigious Meta Research PhD Fellowship 2022 that supported the work on the here presented dissertation.
5. The paper "Are Embodied Avatars Harmful to our Self-Experience? The Impact of Virtual Embodiment on Body Awareness" has received an Honorable Mention at CHI 2023.

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List of Abbreviations

AMT Active Modification Task
AR Augmented Reality
BMI Body Mass Index
CaP Congruence and Plausibility
HMD Head-Mounted Display
IK Inverse Kinematic
IPQ Igroup Presence Questionnaire
MR Mixed Reality
OST Optical See-Through
PET Passive Estimation Task
SOD Self-Observation Distance
SoE Sense of Embodiment
SoP Sense of Presence
UX User Experience
VBO Virtual Body Ownership
VE Virtual Environment
VEQ Virtual Embodiment Questionnaire
VHPQ Virtual Human Plausibility Questionnaire
VR Virtual Reality
VST Video See-Through
XR eXtended Reality

As the dissertation's chapters follow already published works, the abbreviations used there may differ slightly.